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Carnegie Institution of Washington

CONTRIBUTIONS

FROM THE

MOUNT WILSON SOLAR OBSERVATORY

VOLUME I

NOS. 1-30

WITH FIFTY PLATES

FEBRUARY, 1905—NOVEMBER, 1908

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Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 1

A STUDY OF THE CONDITIONS FOR SOLAR RESEARCH AT MOUNT WILSON, CALIFORNIA[1]

By GEORGE E. HALE, Director

In 1902, Dr. S. P. Langley addressed a communication to the Carnegie Institution recommending the establishment of an observatory at a very high altitude for the special purpose of measuring the solar radiation. In this communication Dr. Langley offered reasons for his belief that the solar radiation may undergo changes of intensity corresponding with those great changes of solar activity which are so strikingly illustrated in the sun-spot cycle. This communication was referred to an advisory committee appointed by the Carnegie Institution to report on various astronomical projects which had been submitted. The committee consisted of Professor E. C. Pickering, chairman; Professor Lewis Boss, Dr. S. P. Langley, Professor Simon Newcomb, and the writer. In its report to the Carnegie Institution, the committee expressed its approval of Dr. Langley's proposal and recommended, in case the Institution felt inclined to pursue the matter further, that a special committee be appointed to make a detailed report on the requirements of a complete solar observatory. It was also recommended that a project for an observatory in the southern hemisphere be investigated and reported upon by the same committee.

As a result of this recommendation, a committee, consisting of Professor Lewis Boss, chairman; Professor W. W. Campbell, and the writer, was appointed in December 1902 to report upon the proposed southern and solar observatories. The report of this committee may be found in *Year Book* No. 2 of the Carnegie Institution. This report also includes a detailed account by Professor W. J. Hussey of his telescopic tests of atmospheric conditions at sites in southern California and Arizona, where he had been sent by the committee. Professor Hussey strongly recommended, as the result of his tests, that Mount Wilson, near Pasadena, Cal., be chosen as the site of the proposed solar observatory, in case the Carnegie Institution decided to establish it.

[1] *Year Book No. 3 of the Carnegie Institution of Washington.*

My first visit to Mount Wilson was made in company with Professor Campbell in June 1903. Professor Hussey had practically completed his tests and desired that we should see for ourselves the conditions he had found. Previous observations of the Sun at Pike's Peak, Mount Etna, and Mount Hamilton had in no wise prepared me for my experience on Mount Wilson. On certain occasions, it is true, I had seen the solar image sharply defined on Mount Etna in the very early morning hours. On Mount Hamilton, also, the solar image is sometimes good; but the testimony of those who have observed the Sun there was decidedly unfavorable. It was therefore with intense satisfaction that on each of the four days of my stay on Mount Wilson I found the definition of the solar image almost perfect, to be rated at from 8 to 9 on a scale of 10.

This visit was necessarily a hurried one, and it was evident that before Mount Wilson could be determined upon as the best available site for an observatory, observations extending over a long period of time would be necessary. As circumstances required that my family should spend the winter of 1903–4 in southern California, I decided to take this opportunity to make a more complete test of atmospheric conditions on Mount Wilson. Before arrangements had been made for living upon the mountain, I made frequent trips from Pasadena to Mount Wilson during the months of December, January, and February, observing the Sun on each occasion with a telescope of 3¼ inches aperture, and noting the prevailing weather conditions. The extraordinary absence of wind, which had seemed so characteristic a feature of the mountain during Professor Hussey's visit, could not be said to continue throughout the winter months. High gales sometimes occur at this season, and the average wind velocity is greater than during the summer. Nevertheless, the wind during the day was usually very light, and on many occasions the quiet days of the previous June seemed to be almost exactly duplicated, except that the temperature was lower. For weeks together not a cloud would be seen in the sky, and the summer serenity was in some measure retained until well into January. Later it was broken by storms, but these practically ended with April.

As the solar definition proved to be surprisingly good for this season of the year, I was soon convinced that Mount Wilson offered exceptional opportunities for both solar and stellar work and that a systematic test of conditions should be inaugurated at the earliest possible moment. Accordingly, I commenced on March 1 to render habitable an old log cabin on the mountain that had been in a state of partial ruin for many years. The cabin, known locally as the "Casino," became our headquarters, where we have lived throughout our work on Mount Wilson. Tests of the solar definition were made as often as possible with the telescope already mentioned, and on April 15 several meteorological instruments provided by the Carnegie Institution were installed. Since that time, with only such interruptions as have been made necessary by the enforced absence of the observers, the instruments have been read at stated hours by Mr. Ferdinand Ellerman or Mr. W. S. Adams, who have also made regular tests of the seeing with the telescope mentioned above.

Through important financial assistance rendered by Mr. Arthur Orr, of Evanston, Ill., and Mr. John D. Hooker, of Los Angeles, and the exceptional facilities kindly granted by the Atchison, Topeka & Santa Fé Railway Co., through President Ripley, it became possible to bring from the Yerkes Observatory the small cœlostat which had previously been sent to the eclipses of 1900 (North Carolina) and 1901 (Sumatra). It had been my purpose to bring out the Snow telescope, but lack of sufficient funds prevented me from doing so. The smaller cœlostat was accordingly erected on the mountain, where it yielded excellent photographs of the Sun, amply sufficient to give objective evidence of the high quality of the observational conditions.

During my first visit to Mount Wilson the only unfavorable feature was the presence of fine dust in the air, which was conspicuous not only in the valley below, but also seemed to extend to a considerable altitude above the mountain. This was by no means sufficient to affect greatly the transparency of the sky, except very near the horizon. Nevertheless, the Milky Way did not stand out with the degree of contrast which one expects to see in a very transparent atmosphere. On my return trip to Chicago through the San Gabriel Valley the dust seemed so conspicuous that I feared it might prove an important objection to Mount Wilson as a site for an observatory. In most classes of solar observation dust does not play a very important part, and the great steadiness of the image would far outweigh any objections which might result from this cause. But in other classes of work which were contemplated for the proposed observatory, this dust, if persistent, would inevitably prove a serious obstacle. For example, in determinations of the value of the solar constant and in the photography of faint nebulæ, the absorption and scattering of light produced by dust in the atmosphere may interfere greatly with the work. It accordingly seemed that special attention should be given to the question of dust in the atmosphere above Mount Wilson. It has fortunately turned out, as will be shown later, that the presence of any appreciable amount of dust in the air above the mountain is so exceptional a phenomenon as to constitute no important objection to Mount Wilson as an observatory site.

After a brief statement regarding the conditions found at Mount Wilson had been presented to the Executive Committee of the Carnegie Institution, in April 1904, they decided to make a grant of a sum sufficient to provide for the erection and use of the Snow telescope on the mountain. The Yerkes Observatory loaned the telescope, and the University of Chicago provided the salaries of some of the observers. The work accomplished on the mountain since this grant was made has been sufficient to serve as a reliable basis for estimates on the cost of a large solar observatory, besides giving valuable experience regarding the necessary methods and cost of construction under the unusual conditions existing at the summit of a mountain nearly 6,000 feet in height. In view of their bearing on the question of a solar observatory, I have accordingly included in my report some remarks on the principal obstacles encountered and overcome in the construction of buildings and the transportation of instruments and materials.

REQUIREMENTS OF A SITE FOR A SOLAR OBSERVATORY

It is desirable to recapitulate here the purposes and plans for a solar observatory which were given at some length in *Year Book* No. 2 of the Carnegie Institution. At the outset, it should be stated that the term "solar observatory" is used here in a broad sense, since it is not intended to exclude from the program certain investigations of stars which are of fundamental importance in any general study of the problem of stellar evolution. For the Sun is a star, comparable in almost every respect with many other stars in the heavens, and rendering possible, through an intimate knowledge of its own phenomena, the solution of some of the most puzzling questions in the general problem of stellar evolution. Conversely, however, the stars are suns, and if we would know the past and future conditions of the Sun, we must examine into the physical condition of stars which represent earlier and later stages of development. It will be seen that there is ample ground for the inclusion in the equipment of a solar observatory of certain instruments especially designed for the study of stellar problems.

The plan of work proposed for the observatory, as outlined in *Year Book* No. 2, includes the following classes of observations:

1. Frequent measurements of the heat radiation of the Sun, to determine whether there may be changes during the sun-spot cycle in the amount of heat received from the Sun by the Earth and in the relative radiation of the various portions of the solar surface.

2. Studies of various solar phenomena, particularly through the use of powerful spectroscopes and spectroheliographs.

3. Photographic and spectroscopic investigations of the stars and nebulæ with a very powerful reflecting telescope, for the principal purpose of throwing light on the problem of stellar evolution.

The present opportunity for important advances in these three departments of research is very unusual. Since the publication of *Year Book* No. 2, Dr. Langley has offered reasons to believe that an actual change in the amount of heat emitted by the Sun occurred in March 1903. It is hardly necessary to say that a change in the intensity of the Sun's heat, if actually established, might have a most important bearing upon many questions relating to the Earth, and, at the same time, be of capital interest in its relationship to the problem of the solar constitution. Through the force of circumstances, Dr. Langley's observations have been made under the very unfavorable conditions which obtain at Washington. If they could be continued at a considerable altitude, at a point above the denser and more fluctuating region of the Earth's atmosphere, the question as to what changes actually occur in the solar radiation could doubtless be answered in a thoroughly satisfactory manner.

In the study of the phenomena of the Sun's surface and atmosphere we again enter a remarkably fruitful field of research. Within the past few years the instruments available for work in this field have been greatly developed, and now only await application on a large scale in order to secure a great number of new results which have hitherto been entirely out of reach. But even if the means were available for supplying the necessary instruments to existing observatories, they could not be successfully employed without atmospheric conditions much superior to those at present available. In work of this nature, success depends upon the perfect definition of the solar image and the absence of those disturbances from which the amosphere at existing observatories is almost never free. For this work, therefore, an elevated station in a region of great atmospheric calm is absolutely essential. Furthermore, the site must be free from the disturbing factors which frequently prevent good observations from being obtained on mountain summits.

In the third class of investigations required to complete the program of a properly equipped solar observatory, similar possibilities of advance exist. Within the past few years the remarkable advantages of the reflecting telescope have been demonstrated. It now only remains to construct a large and powerful instrument of the type shown by these experiments to promise success. With such an instrument, immense new fields of investigation of the highest importance in their bearing on the problem of stellar evolution could be immediately occupied. Here again, however, the unfavorable atmospheric conditions at almost all existing observatories would render the construction of a large telescope almost useless. To be successful, such an instrument must be erected at a site where the night-seeing is nearly perfect, the sky clear and transparent, and the average wind velocity very low. Under such conditions, a properly constructed telescope of large aperture would undoubtedly yield results greatly surpassing those hitherto obtained.

These considerations are sufficient to define the general character of a site suitable for a well-equipped solar observatory. There are other points, however, which must be taken into account. A solar observatory provided with an outfit of instruments, and then left to do its work without the possibility of improvement or change, could never attain the best results. On the contrary, it must have the means of producing new types of instruments and modifying old ones, as the development of the work may suggest. In other words, a shop completely equipped with all appliances necessary for the most refined construction of both the mechanical and optical parts of instruments should form an integral part of a solar observatory. A shop of this kind cannot be conducted without great difficulty and expense, if far removed from large cities and other sources of supply. This is only one of many reasons which would render it desirable to select an observatory site within easy reach of the facilities afforded by a large city.

In his recommendation for the establishment of an observatory for the purpose of determining whether the heat radiation of the Sun undergoes change, Dr. Langley pointed out the desirabliity of making the observations at a height of some 20,000 feet above sea-level. Apart from the excessive difficulty and expense of conducting an observatory at such an elevation, which are best appreciated by those who have worked at great altitudes, the inaccessibility of high mountain peaks would stand in the way of such an undertaking. But it nevertheless might have been carried out, at a somewhat lower altitude, if the recent development of Dr. Langley's work at Washington had not indicated that the great mass of observations could undoubtedly be made to good advantage at a much lower station. The increasing perfection of the observational method has, indeed, permitted fairly good results to be obtained under the very unfavorable conditions which exist at Washington. Nevertheless, it by no means follows that Dr. Langley's purpose could be accomplished at such a point. The humidity of our atmosphere is a most serious obstacle in this particular work, since the solar heat is very subject to absorption by water vapor. It is therefore desirable to establish the instruments a least a mile above the dense and disturbed layers of the atmosphere which lie near the sea-level. Certain problems connected with the investigation may render it desirable to make some of the observations at a higher altitude, reaching from 12,000 to 15,000 feet. We conclude, therefore, that the principal work should be done at a station having an elevation of 5,000 to 6,000 feet, in a dry climate, where the weather is continuously clear over long periods of time. The work at higher altitudes, if needed at all, could in all probability be completed in two or three summers by expeditions equipped with a portable outfit erected at an altitude of from 12,000 to 15,000 feet It would thus be convenient to have the principal station at a lower altitude, not far removed from accessible mountains of this considerable elevation. It would be inadvisable, for reasons which it is hardly necessary to specify, to establish the principal station at an altitude much greater than 6,000 feet.

POSITION AND NATURAL RESOURCES OF MOUNT WILSON

From a meteorological standpoint, the state of California may naturally be divided into three parts. In the northern region the rainfall is very considerable, much cloudiness prevails, and in almost all respects the conditions are very unfavorable for astronomical work. The central region, which may be considered to extend as far south as Point Concepcion, is favored with much better weather conditions, best exemplified at the Lick Observatory, on Mount Hamilton, where a high average of night-seeing is maintained during a large part of the year. Except for the frequent winds at night, which interfere with some classes of work, Mount Hamilton might be regarded as an almost ideal observatory site, at least for night observations. For solar work it may not be superior to certain stations in the eastern part of the United States, because of the excessive radiation from the heated slopes of the mountain, which is almost devoid of trees near the summit.

In the southern part of California the climatic conditions are decidedly different from those which prevail in the two other sections of the state. The much lighter rainfall is naturally associated with fewer clouds, a remarkably steady barometer, and very light winds. During a part of the year the fog rolls in from the ocean and covers much of the San Gabriel Valley during the night. But these fog-clouds rarely attain elevations exceeding 3000 feet, except when storm conditions prevail during the winter months. The mountains of the Sierra Madre range rise high above the fog, and during a great proportion of the year they enjoy practically continuous sunshine. During the summer months the sea breeze blows for a large part of the day, but it attains only a low velocity, which decreases in passing from the valley to the mountain tops and in going inward from the coast.

Mount Wilson is one of many mountains that form the southern boundary of the Sierra Madre range. Standing at a distance of thirty miles from the ocean, it rises abruptly from the valley floor, flanked only by a few spurs of lesser elevation, of which Mount Harvard is the highest. Except for a narrow saddle, Mount Wilson is separated from Mount Harvard by a deep cañon, the walls of which are very precipitous. Farther to the west, beyond the saddle leading to Mount Harvard, the ridge of Mount Wilson forms the upper extremity of Eaton Cañon, which leads directly to the San Gabriel Valley. East and north of Mount Wilson lies the deep cañon through which flows the west fork of the San Gabriel River, and beyond this rises a constant succession of mountains, most of them higher than Mount Wilson, which extend in a broken mass to the Mojave Desert. The Sierra Madre range forms the northern boundary of the San Gabriel Valley, which is further protected toward the east from the desert by the high peaks of the San Bernardino range. Through the Cajon Pass, where the Atchison, Topeka & Santa Fé Railroad enters the valley, winds from the desert frequently blow, bringing vast quantities of dust, which sometimes diffuses through the lower air over the entire valley. This dust but rarely reaches an elevation as great as that of Mount Wilson, though I have seen a few windstorms that carried the dust of the desert directly over the Sierra Madre range and into the valley below.

For the most part, the readily accessible mountains on the southern boundary of the Sierra Madre range have few trees near the summit, and enjoy but small supplies of water. Mount Wilson is remarkable in having a fine growth of trees covering its summit, and in possessing within easy reach of its highest point several large springs of water, which afford a good supply even during very dry seasons.

In a dry country the question of a pure and permanent supply of water is of paramount importance. It is therefore desirable to give more definite information of the springs near the summit of Mount Wilson. Some of these are located at Strain's Camp, where, for many years, they have supplied the necessities of summer visitors, who frequently occupy tents here for considerable periods of time. Two wells have been dug at Strain's Camp, and these are regarded as excellent sources of pure water.

In accordance with the terms of the lease of the property at present occupied as an observatory site on Mount Wilson, the water rights on the mountain are to be equally divided between the owners of the property and the occupants of the observatory site. It seems probable that the wells at Strain's Camp, if properly developed, would supply the purposes of a large observatory. If not, more water could easily be developed on the mountain; it may appear desirable to obtain water from a stream in one of the neighboring cañons, about 1000 feet below. The expense of pumping to this height would be great, and the stream can be relied upon as a never-failing source of water. A water-tunnel on the south face of the mountain has been reserved by the owners of the property for the purpose of supplying Martin's Camp, and is not included in the equal division of the remaining water rights. A method of securing more water, which could undoubtedly be employed with advantage, would be through the use of large storage tanks, in which water could be collected during the rainy season, either by pumping from the overflowing wells or by catching the rain as it falls on roofs or other large surfaces provided for the purpose.

TRANSPORTATION AND CONSTRUCTION

Much granite is available on Mount Wilson for the purpose of construction, but in the portion of the mountain selected for the observatory site it is not so easily obtained as might be wished. This is due to the fact that much of the granite is decomposed, and consequently too soft for building purposes. The hard and the decomposed granites occur together, so that if a quarry is started at a point where plenty of hard granite seems to be present, it sometimes happens that the supply is soon exhausted, leaving only decomposed granite below. Men experienced in matters of this kind have been quite unable to judge whether selected spots could be relied upon to furnish a good supply of hard granite. This fact greatly increases the expense of constructing stone piers, since quarries may have to be abandoned after having been opened at considerable cost. However, some abundant sources of excellent stone can be rendered easily accessible by the extension of roads constructed for work now in progress.

Numerous fallen trees on Mount Wilson, which are not yet greatly decayed, will furnish an abundant supply of firewood for many years to come. They cannot be depended upon, however, to yield any wood for building purposes, and as the living trees may not be destroyed, all lumber must be taken to the summit of the mountain from Pasadena. This raises the question of transportation over the mountain trail—a matter of vital importance in constructing an observatory. The "Toll Road" or "New Trail," which extends from the summit of the mountain to the foot of Eaton Cañon, is well adapted for all ordinary packing with animals, though it is much too narrow to permit wagons to pass over it. At present, all except the heaviest articles are taken to the summit of the mountain by means of burros and pack-mules, each of which can carry a load ranging from 80 to 200 pounds. It is evident that transportation of building materials by this means must be very slow and expensive, since the trail is nine miles in length to the foot of Eaton Cañon, six and one-half miles distant by road from Pasadena. But, as compared with most mountains, Mount Wilson is unusually accessible from cities, Pasadena being so close at hand, and Los Angeles, with its large sources of supply, being only nine miles farther away.

For transporting heavy castings and other similar articles, we have found it necessary to construct a special four-wheel carriage, two feet in width. On this loads of a thousand pounds have been taken to the summit without difficulty. By widening the trail to six feet, the heaviest castings required for a solar observatory probably could be transported.

WEATHER

So far as cloudiness is concerned, the records of the Weather Bureau at Los Angeles are of comparatively little value for our present purposes. The fog rolls in from the ocean night after night, and sometimes hangs over Los Angeles throughout the day during the winter season. But Mount Wilson reaches far above this layer of clouds, and thus frequently enjoys sunshine when the valley below is completely covered. Our daily percentage record of cloudiness, beginning on April 18, 1904, may be found in the following table. A dash signifies that no observation was made.

There were many days which were cloudy at the time of observation, but nevertheless suitable at other hours for solar work. Adding these to the record, it may be said that the actual number of days on

CLOUDINESS

Day of Month	April		May		June		July		August	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1........	...	...	100	20	75	75	0	0	0	0
2........	...	...	0	5	5	0	0	0	0	0
3........	...	...	0	0	0	0	0	0	90	10
4........	...	...	0	0	0	0	0	0	5	25
5........	...	...	0	0	0	0	0	0	0	0
6........	...	...	0	0	0	0	0	0	30	100
7........	...	...	0	0	0	0	0	—	40	60
8........	...	...	0	0	0	0	0	10	50	40
9........	...	...	70	85	0	0	0	—	0	0
10........	...	...	5	5	0	0	—	—	0	0
11........	...	...	0	0	0	0	0	0	0	0
12........	...	...	0	0	0	0	0	0	30	50
13........	...	...	0	0	0	0	0	0	20	20
14........	...	...	0	0	0	0	0	0	80	80
15........	...	...	0	0	0	25	0	0	0	0
16........	...	...	0	0	5	0	0	—	0	5
17........	..	...	0	0	0	0	—	—	0	0
18........	...	...	0	0	0	10	—	0	10	5
19........	100	100	0	0	0	0	0	0	0	0
20........	50	5	0	75	0	0	5	5	0	0
21........	0	0	25	5	0	0	—	50	0	5
22........	70	100	0	50	0	0	45	5	75	80
23........	0	0	5	5	0	0	35	5	20	30
24........	0	5	0	0	0	0	5	10	60	5
25........	75	0	100	100	0	0	35	15	5	5
26........	100	100	100	0	0	0	20	15	5	5
27........	0	100	0	0	0	0	12	7	0	5
28........	80	100	0	0	0	0	15	5	0	5
29........	0	0	10	75	0	0	10	5	0	5
30........	0	—	0	0	0	0	5	—	5	80
31........	...	...	0	0	...	...	—	—	80	5

which observations could be made amount to 132 out of 135. The long periods of perfectly clear weather, permitting observations of the Sun to be made without interruption from day to day, should prove of the greatest importance in the study of many solar problems which require daily observations for their solution. From the records so far obtained, it seems probable that observations of the Sun could be made at Mount Wilson on more than 300 days in a year. In Los Angeles, during the past twenty-three years, the average number of "clear" days in the year is 317.

CLOUDINESS

Day of Month	September		October		November		December	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1	0	0	15	10	80	90	100	100
2	0	0	0	0	0	0	100	100
3	0	5	15	60	0	0	0	5
4	0	60	80	50	5	40	80	25
5	0	40	0	50	3	60	5	3
6	5	0	100	100	20	20	0	0
7	0	0	100	100	0	30	5	3
8	0	5	100	—	30	0	5	3
9	10	60	—	—	0	5	5	95
10	0	0	—	10	15	5	0	0
11	0	5	60	40	3	0	10	25
12	0	60	0	0	80	70	—	0
13	0	5	0	0	80	5	10	70
14	0	0	0	0	7	75	20	50
15	3	15	20	10	95	50	40	40
16	60	3	0	0	5	0	5	0
17	50	40	0	0	0	0	10	3
18	20	5	0	0	15	0	5	0
19	40	50	0	0	5	0	0	5
20	70	40	0	0	3	10	15	50
21	75	95	0	0	60	15	90	95
22	100	30	0	0	10	3	100	10
23	100	100	0	0	0	5	90	5
24	100	100	0	0	—	—	100	100
25	100	100	0	3	—	15	5	5
26	100	98	0	0	50	30	—	—
27	—	—	0	0	70	10	—	—
28	—	0	0	3	5	5	0	5
29	0	40	0	15	0	3	60	0
30	0	3	50	3	20	40	3	95
31	..	..	0	0	..	..	100	30

The cloudiness in July and August was due almost entirely to thunderstorms over the desert to the north and east. The clouds rarely reached our zenith and almost never interfered with the regular solar observations (cf. table of Seeing).

HUMIDITY

The question of humidity is of special importance in connection with the measurement of the solar constant, since water-vapor in the atmosphere absorbs very strongly the solar heat. The results obtained with a standard sling psychrometer, Weather Bureau pattern, are given in the following table:

RELATIVE HUMIDITY AT MOUNT WILSON

DAY OF MONTH	APRIL		MAY		JUNE		JULY		AUGUST	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1	..	..	100	80	40	36	34	24	22	27
2	..	..	57	80	39	39	23	38	22	33
3	..	..	34	66	39	41	30	32	29	30
4	..	..	46	49	24	25	38	56	32	40
5	..	..	38	38	20	24	34	42	40	43
6	..	..	29	40	27	42	45	43	34	43
7	..	..	36	31	29	41	49	—	—	76
8	..	..	18	22	23	29	33	18	64	58
9	..	..	15	24	20	34	42	—	41	46
10	..	..	22	41	21	21	—	—	28	35
11	..	..	36	38	19	17	57	24	30	33
12	..	..	36	54	—	—	29	40	53	65
13	..	..	41	40	—	43	46	22	61	64
14	..	..	32	64	52	42	25	25	67	72
15	..	..	23	29	32	30	30	44	54	45
16	..	..	27	19	34	30	50	—	37	36
17	..	..	34	38	33	24	—	—	40	30
18	—	85	25	66	32	41	—	16	34	45
19	100	100	46	64	31	42	22	24	32	46
20	96	73	41	100	56	72	21	19	23	40
21	60	79	42	45	45	53	—	42	37	33
22	92	98	28	43	40	43	24	34	58	85
23	63	65	37	32	44	54	35	35	79	79
24	60	50	38	50	42	32	31	26	77	56
25	29	68	100	100	30	27	33	50	69	58
26	100	100	100	48	28	25	38	27	67	37
27	100	100	37	38	27	36	31	50	40	43
28	100	100	38	33	42	35	30	32	43	33
29	46	36	23	15	35	30	50	46	21	29
30	58	71	14	47	30	37	38	—	27	14
31	..	..	30	35	..	..	—	—	14	31
Means	77		43		34		33		43	

The marked dryness of the atmosphere on Mount Wilson during the summer months may be best appreciated by comparing these results with those obtained by the Weather Bureau at Washington during the corresponding period.

RELATIVE HUMIDITY AT WASHINGTON

Month	Mean	Maximum[1]	Minimum[1]
April	63.0	100	30
May	65.6	97	41
June	77.8	98	54
July	60.6	99	51
August	78.0	95	59

[1] Mean maximum and mean minimum humidity not determined.

RELATIVE HUMIDITY AT MOUNT WILSON

Day of Month	September		October		November		December	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1	26	29	47	38	62	46	100	100
2	38	24	49	48	84	89	100	100
3	31	38	42	37	72	83	70	57
4	43	43	60	63	71	53	63	49
5	31	22	69	100	49	53	58	52
6	22	25	100	100	63	57	53	47
7	20	18	100	100	38	57	59	43
8	30	40	100	—	52	35	47	59
9	41	39	—	—	37	51	57	51
10	53	48	—	86	56	61	12	14
11	48	45	100	100	54	26	12	17
12	60	63	53	56	48	44	19	42
13	57	63	53	47	61	30	48	43
14	51	28	56	60	22	21	33	30
15	37	43	67	77	28	56	18	—
16	41	27	67	55	57	50	—	21
17	32	66	49	54	72	41	20	30
18	54	78	44	52	71	81	26	35
19	60	37	59	66	59	35	42	28
20	46	49	67	68	60	34	29	34
21	32	67	33	31	69	29	42	65
22	93	93	20	27	59	57	100	84
23	94	100	22	34	55	47	91	95
24	100	100	24	28	—	—	100	100
25	100	100	23	27	—	32	81	81
26	100	80	26	34	65	41	—	—
27	—	—	29	47	31	29	—	—
28	—	64	46	71	53	50	56	45
29	60	52	41	66	36	40	50	56
30	57	47	66	81	49	62	38	90
31	..	..	78	40	..	..	100	83
Means	52		57		51		55	

The chief of the Weather Bureau has also kindly sent the following data as to the mean relative humidity at Washington for the remainder of the year. The two values refer to the results for 8 A. M. and 8 P. M., respectively. September, 84.8, 78.2; October, 80.8, 71.7; November, 76.2, 66.9; December, 77.8, 70.6.

TEMPERATURE

From March 25 to April 15 the temperature was recorded on a self-registering thermometer. After April 15 this record was supplemented by observations of maximum and minimum thermometers.

The results are given (in degrees Fahrenheit) in the following table. As bearing upon certain classes of night observations, the range of temperature between 8 P. M. and 4 A. M. is also included.

TEMPERATURE

Day of Month	April			May			June			July			August		
	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.
1.....	..	..	..	49	32	8	76	46	4	93	57	5	83	57	3
2.....	..	..	..	56	27	4	82	53	1	81	58	5	90	63	5
3.....	..	..	..	64	39	4	89	55	2	79	56	8	91	66	3
4.....	..	..	..	70	42	5	80	56	7	80	56	3	89	66	5
5.....	..	..	..	79	45	7	81	59	5	77	54	6	91	66	2
6.....	..	..	..	80	55	2	78	57	6	75	55	6	92	68	2
7.....	..	.	..	84	51	8	75	48	9	—	—	5	—	—	6
8.....	..	..	..	84	55	7	79	52	3	76	52	6	83	64	3
9.....	..	..	..	85	57	5	83	57	4	—	—	2	87	60	6
10.....	.	..	..	86	57	5	82	61	5	—	—	2	86	64	4
11.....	..	..	.	79	57	2	87	60	4	82	57	5	87	63	4
12.....	..	..	.	85	54	2	—	—	5	86	56	4	88	62	5
13.....	..	..	..	75	56	4	—	—	5	89	59	3	85	64	3
14.....	..	..	..	79	50	6	77	57	6	83	63	7	83	60	3
15.....	..	..	..	85	53	4	80	54	4	75	57	4	86	60	2
16.....	..	..	..	82	57	4	79	53	5	72	50	4	87	60	5
17.....	..	..	..	79	56	5	81	56	5	84	63	6	87	62	5
18.....	53	37	6	75	49	4	83	55	8	93	61	1	88	63	4
19.....	42	35	3	56	36	8	79	59	5	95	66	3	93	64	5
20.....	41	23	6	74	45	1	73	51	7	91	69	1	90	65	5
21.....	49	34	1	78	50	5	86	50	1	—	—	2	86	59	8
22.....	46	32	5	81	51	4	83	55	2	82	62	4	77	60	2
23.....	49	25	9	78	56	3	78	55	6	89	62	2	78	56	2
24.....	63	36	3	69	54	4	78	53	6	91	66	3	81	56	0
25.....	64	40	4	52	38	10	87	56	3	88	68	4	85	61	2
26.....	43	29	8	53	35	3	88	62	1	82	66	3	89	62	3
27.....	43	23	4	69	41	0	85	63	5	88	62	2	87	64	2
28.....	44	31	0	75	49	5	79	57	4	83	68	5	87	62	2
29.....	63	36	2	71	50	5	79	55	3	83	62	7	87	62	2
30.....	65	41	5	70	46	6	78	53	5	—	—	3	81	59	4
31.....	—	—	—	77	45	4	—	—	—	—	—	4	82	59	3
Means	51.2	32.7	4.3	73.5	48.0	4.7	80.9	55.3	4.5	84.0	60.2	4.0	86.2	61.9	3.5
Daily r'ge	18.5		....	25.5		....	25.6		....	23.8		....	24.3		....

TEMPERATURE

Day of Month	September			October			November			December		
	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.
1	87	60	3	79	60	5	75	48	2	60	38	4
2	90	66	2	83	54	5	63	42	7	48	36	4
3	91	66	3	84	55	4	78	40	3	59	33	4
4	89	63	5	87	59	2	71	46	3	64	35	2
5	93	65	5	66	47	3	70	45	2	60	29	7
6	97	67	4	56	37	8	72	46	1	63	31	3
7	97	69	4	49	39	2	80	49	3	64	33	2
8	87	68	5	—	—	0	84	49	2	61	37	1
9	87	63	7	—	—	2	82	51	2	66	37	2
10	83	59	7	67	—	2	82	52	3	74	41	1
11	83	59	3	56	43	7	76	47	5	72	42	4
12	86	57	3	72	36	4	69	49	7	68	37	5
13	85	58	4	74	45	4	72	42	3	70	36	4
14	87	58	1	71	48	5	72	48	1	66	44	1
15	83	59	2	67	43	5	64	44	3	—	44	5
16	81	59	3	75	43	4	74	38	6	66	52	—
17	74	50	4	75	39	6	73	47	2	65	41	2
18	71	44	5	77	42	2	67	45	3	67	49	2
19	78	49	2	82	46	3	76	42	5	69	42	3
20	76	50	3	84	46	4	78	47	2	67	50	2
21	72	52	3	81	50	4	80	50	3	60	39	3
22	51	41	7	83	53	4	73	50	3	44	32	5
23	51	39	4	79	54	4	72	49	2	45	33	2
24	54	41	2	82	54	2	—	—	1	41	35	2
25	52	43	1	82	54	3	72	—	1	50	31	5
26	52	36	6	78	52	3	77	51	3	—	—	3
27	—	—	2	74	47	6	73	52	2	—	—	3
28	75	—	3	72	47	3	73	50	3	56	34	5
29	82	50	3	67	47	1	75	49	2	59	44	3
30	81	52	5	67	46	2	72	45	2	54	38	4
31	..	..	..	75	43	3	..	..	..	43	33	4
Means	78.4	55.1	3.7	73.9	47.5	3.6	74.0	46.9	2.9	60.0	38.1	3.1
Daily range	23.3			26.4			27.1			21.9		

ATMOSPHERIC PRESSURE

No complete barometric record has been kept, since this did not seem of special importance in connection with the work. Nevertheless, an aneroid barometer has been read twice daily since July 13. The maximum and minimum readings recorded up to September 1 differed by only 0.22 inch.

WIND MOVEMENT

With such uniformity of atmospheric pressure, it might naturally be anticipated that the wind movement would be low. The results of anemometer readings (in miles), made with an instrument of the standard Weather Bureau pattern, are shown in the following table. The "day" results give the total movement from 8 A. M. to 6 P. M.; the "night" results give the total movement from 6 P. M. to 8 A. M.

Day of Month	April		May		June		July		August	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
1	...	...	99	75	120	175	55	145	43	95
2	...	...	49	165	71	141	71	102	50	72
3	...	...	52	118	44	185	47	71	45	61
4	...	...	29	88	44	114	34	41	46	48
5	...	...	43	91	61	47	30	54	60	41
6	...	...	30	62	78	108	43	78	43	49
7	...	...	34	128	59	155	40	44	47	80
8	...	...	43	106	55	146	49	85	33	63
9	...	...	38	44	50	66	44	83	43	60
10	...	...	44	133	52	86	43	77	62	78
11	...	...	54	110	43	49	49	93	49	81
12	...	...	35	101	32	75	31	74	58	122
13	...	...	41	80	30	95	42	81	59	71
14	..	...	39	95	23	133	42	59	44	73
15	...	...	72	114	49	61	39	68	44	55
16	...	. .	42	110	56	80	33	50	45	80
17	...	...	46	81	40	58	40	70	44	60
18	. .	...	50	56	37	56	32	62	26	55
19	140	188	105	136	30	47	38	78	37	58
20	62	70	45	48	36	74	63	91	36	100
21	35	144	63	71	56	90	37	60	39	55
22	40	42	66	82	37	56	43	37	63	104
23	47	120	67	97	74	103	44	85	63	113
24	32	109	69	79	44	86	60	64	55	101
25	70	63	63	136	52	51	44	56	50	64
26	91	191	33	60	55	59	39	71	35	66
27	44	51	50	58	75	51	47	80	56	84
28	33	34	21	101	42	52	41	57	54	107
29	50	101	62	73	37	60	56	65	55	56
30	47	63	51	80	56	46	57	131	57	69
31	...	...	57	151	...	...	53	97	38	54
Total	691	1,176	1,592	2,929	1,538	2,605	1,386	2,309	1,479	2,275
Means	57.6	96.0	51.3	94.5	51.3	86.6	44.7	74.5	47.7	73.4
Hourly means	5.8	6.8	5.1	6.7	5.1	6.2	4.5	5.3	4.8	5.2

It appears from these results that the average wind movement is exceptionally low. The importance of this fact in its indication of a uniform atmosphere, and in connection with astronomical photog-

WIND MOVEMENT

Day of Month	September		October		November		December	
	Day	Night	Day	Night	Day	Night	Day	Night
1	34	76	43	60	61	71	27	81
2	51	30	39	32	42	123	36	70
3	52	67	38	58	44	130	34	82
4	40	70	50	81	55	47	42	137
5	49	71	58	100	38	88	80	120
6	50	97	44	125	41	95	40	141
7	51	48	85	56	38	64	42	78
8	50	88	—	129	48	97	36	62
9	47	68	—	—	41	144	38	66
10	35	54	—	—	36	151	66	106
11	37	53	68	86	32	45	37	59
12	42	44	40	102	35	148	65	165
13	46	73	41	52	25	53	38	154
14	47	71	53	83	49	46	38	56
15	66	86	40	117	35	105	53	69
16	73	81	50	79	37	71	39	68
17	51	101	89	207	56	93	31	56
18	33	91	50	139	44	92	31	53
19	38	83	65	128	39	48	33	64
20	36	71	47	194	29	51	37	51
21	80	52	37	125	39	73	85	74
22	37	110	46	45	59	110	64	101
23	83	84	45	44	65	141	36	46
24	72	161	36	74	—	—	82	113
25	70	163	38	66	—	—	66	142
26	64	101	36	55	53	91	—	—
27	—	—	42	49	46	91	—	—
28	—	—	53	62	45	47	37	69
29	64	158	64	94	47	73	57	48
30	58	53	39	66	65	165	122	146
31	..	..	42	73	..	..	60	200
Means	52.0	82.3	49.2	89.0	44.4	91.2	50.1	92.3
Hourly means	5.2	5.9	4.9	6.4	4.4	6.5	5.0	6.6

raphy, will be appreciated by astronomers. The shaking of a large instrument by the wind is frequently so serious as to reduce greatly the quality of astronomical photographs obtained in windy weather. At Mount Wilson, where a dead calm is an exceedingly common occurrence, all of the most exacting requirements of astronomical photography are completely realized.

TRANSPARENCY OF THE ATMOSPHERE

I have previously alluded to the dust-storms which sometimes enter the San Gabriel Valley through the Cajon Pass from the Mojave Desert, and those much rarer storms in which the dust is carried by the wind completely over the Sierra Madre Mountains. In the more common form of dust-storm (the so-called "Santa Ana") the dust enters the valley in a fairly well-defined mass and proceeds westward along the cañon of the Santa Ana River. In approaching the coast it spreads over a large area and diffuses itself with tolerable uniformity through the lower atmosphere. I have seen from Mount Wilson a dust-storm in the region of Riverside, which in twenty-four hours had spread itself over Los Angeles and Pasadena. When it reached this part of the valley there was almost no wind, and the dust seemed to diffuse itself through the air. Such storms sometimes completely hide the Sierra Madre Mountains from observers in Pasadena. Fortunately they are almost always confined to the lower atmosphere, and do not appreciably affect the transparency of the sky above Mount Wilson, where daily observations show that the transparency of the day and night sky are very satisfactory.

SEEING

Systematic tests of the definition of the solar image have been made on Mount Wilson with a telescope of 3¼ inches aperture, with an eyepiece giving a power of about 100 diameters. At first the character of the seeing was rated on a scale of 5; but it soon appeared that a scale of 10 would be preferable under the existing conditions. Accordingly, the seeing as recorded in the following table is given on a scale of 10. Seeing 8, which is so frequently obtained during the early morning hours, represents a sharply defined image of the Sun, showing the granulation and the details of the spots with great distinctness, and indicating practically no trembling at the limb. Such seeing occurs at the Yerkes Observatory only occasionally, although that observatory seems to be better situated than many other institutions for work on the Sun.

An examination of the table will show that the seeing is best during the early morning hours, although the image is frequently very good in the late afternoon. Shortly after sunrise the Sun's limb is serrated, but this effect becomes less and less marked as the Sun's altitude increases. Usually, at this time in the morning, the atmosphere is almost perfectly calm and cloudless. The seeing usually improves and reaches a maximum, where it remains for some time. The effect

SEEING

APRIL	HOUR OF OBSERVATION								
	6	7	8	9	10-2	3	4	5	6
1...	–	5	5	4	4	4	5	4	–
2...	–	–	5	6	5	5	4	4	–
3...	–	5	6	7	6	–	–	–	–
4...	–	5	6	7	6	3	5	–	–
5...	–	8	8	8	7	–	8	8	6
6...	–	6	7	6	4	7	7	5	–
7...	–	9	8	7	7	6	7	7	5
8...	–	–	7	–	–	–	–	–	–
9...	–	5	5	4	4	4	5	4	–
10...	6	7	7	6	6	7	–	–	–
11...	7	9	7	6	6	7	–	–	–
12...	–	7	7	6	–	–	–	–	–
13...	–	8	8	7	–	–	7	8	7
14...	–	6	6	6	5	5	4	–	–
15...	–	–	–	–	–	–	–	–	–

APRIL	HOUR OF OBSERVATION								
	6	7	8	9	10-2	3	4	5	6
16...	–	5	–	5	–	–	–	4	–
17...	–	–	5	4	4	6	0	–	–
18...	–	6	7	–	–	–	–	–	–
19[1]..	–	–	–	–	–	–	–	–	–
20...	–	6	5	–	–	–	–	–	–
21...	–	6	7	6	5	4	6	6	–
22[1]..	–	–	–	–	4	–	–	–	–
23...	–	–	5	4	4	4	4	–	–
24...	–	–	7	6	5	5	6	6	7
25...	–	–	–	–	4	4	4	4	–
26[2]..	–	–	–	–	–	–	–	–	–
27[1]..	–	6	4	–	–	–	–	–	–
28[1]..	–	6	–	–	–	–	–	–	–
29...	–	7	6	6	4	5	6	–	–
30...	6	7	4	4	4	4	6	–	–

MAY	HOUR OF OBSERVATION								
	6	7	8	9	10-2	3	4	5	6
1[2]..	–	–	–	–	–	–	–	–	–
2...	–	5	4	4	3	2	2	2	–
3...	–	7	6	7	5	4	6	–	–
4...	–	6	6	5	4	5	5	–	–
5...	–	7	–	–	4	5	5	4	–
6...	7	8	6	–	–	–	–	–	–
7...	5	4	4	4	4	4	4	4	–
8...	–	7	7	5	–	–	–	–	–
9[3]..	–	–	5	–	–	–	–	–	–
10...	–	5	6	5	5	–	–	–	–
11...	–	6	5	5	4	–	–	–	–
12...	–	–	–	–	–	–	–	–	–
13...	–	–	–	–	–	–	–	–	–
14...	–	–	–	–	–	–	–	–	–
15...	–	5	6	5	–	–	–	–	–
16...	6	–	–	7	7	–	6	6	–
17...	–	–	–	–	–	–	–	–	–
18...	–	–	–	–	–	–	–	–	–
19...	–	–	–	–	–	–	–	–	–
20...	–	–	–	–	–	–	–	–	–
21...	–	–	–	–	–	–	5	–	–
22...	–	6	7	8	–	4	–	–	–
23...	–	6	–	6	5	–	6	–	–
24...	–	8	–	6	6	–	5	–	–
25[1]..	–	–	–	–	–	–	–	–	–
26[1]..	–	–	–	–	–	–	–	8	–
27...	–	8	7	6	6	7	7	8	–
28...	–	8	8	–	7	–	8	–	7
29...	–	9	8	8	8	–	–	–	–
30...	–	7	8	8	7	6	6	7	–
31...	–	6	7	–	6	6	7	–	–

JUNE	HOUR OF OBSERVATION								
	6	7	8	9	10-2	3	4	5	6
1[3]...	–	–	–	–	–	–	6	–	–
2...	–	–	7	6	6	6	6	6	–
3...	–	6	6	6	6	6	6	6	–
4...	–	6	–	7	5	–	–	–	–
5...	–	8	8	–	7	–	6	–	4
6...	–	9	9	8	7	7	–	–	–
7...	–	7	–	–	4	4	6	–	7
8...	–	8	8	–	6	–	–	7	6
9...	–	9	8	6	6	–	6	7	–
10...	–	9	8	–	7	–	–	7	–
11...	–	9	8	–	6	–	8	7	9
12...	–	9	–	–	–	–	–	–	–
13...	–	–	–	–	–	–	–	–	–
14...	–	–	–	–	–	–	–	8	–
15...	–	9	8	7	6	–	7	7	–
16...	–	9	8	–	7	–	8	7	8
17...	–	9	9	7	7	5	–	7	8
18...	–	8	7	–	5	–	7	8	7
19...	–	9	6	6	4	–	–	7	–
20...	6	6	–	6	5	7	7	–	6
21...	–	6	6	–	5	–	6	–	6
22...	8	–	8	6	6	6	7	8	8
23...	–	8	7	–	7	–	7	8	–
24...	–	9	8	–	6	–	7	8	–
25...	8	9	7	–	7	–	7	7	–
26...	–	9	8	8	6	–	6	6	–
27...	–	8	8	7	7	–	–	5	6
28...	8	8	–	–	6	–	6	6	–
29...	8	9	–	6	6	–	–	8	–
30...	8	9	–	8	8	8	8	8	7

[1] Rain. [2] Snow. [3] Cloudy.

July	Hour of Observation									August	Hour of Observation								
	6	7	8	9	10-2	3	4	5	6		6	7	8	9	10-2	3	4	5	6
1...	–	5	–	6	–	–	6	6	–	1...	–	–	–	6	5	6	7	8	–
2...	–	8	–	–	4	–	–	–	–	2...	6	6	6	–	4	6	7	6	–
3...	–	8	7	–	6	–	–	–	4	3...	–	7	–	–	5	–	7	7	–
4...	–	6	–	7	5	–	–	–	–	4...	–	6	7	7	6	6	6	7	–
5...	8	8	–	–	5	–	7	–	6	5...	–	8	8	–	5	5	–	–	–
6...	–	8	8	–	7	–	–	8	8	6...	8	8	7	6	–	–	–	–	–
7...	–	8	7	–	–	–	–	–	–	7...	–	8	–	–	–	–	–	–	–
8...	8	8	7	–	7	–	–	8	8	8...	–	8	–	–	5	6	6	6	–
9...	8	9	–	–	6	–	–	–	–	9...	6	7	–	6	4	–	7	8	8
10...	–	–	–	–	–	–	–	–	–	10...	6	7	7	–	5	6	–	6	–
11...	–	8	6	–	5	–	7	8	6	11...	7	7	6	–	5	6	–	6	–
12...	8	9	8	–	5	6	7	7	7	12...	6	5	–	–	5	6	–	6	–
13...	8	8	7	7	6	–	–	8	7	13[4]....	6	–	–	–	–	–	–	4	–
14...	8	8	7	–	6	–	7	7	7	14[4] ..	–	7	–	–	–	–	–	–	–
15...	–	7	6	5	4	4	6	7	–	15...	–	7	–	–	–	–	8	–	6
16...	–	5	4	4	–	–	–	–	–	16...	8	7	–	–	4	–	8	–	7
17...	–	–	–	–	–	–	–	–	–	17...	–	8	7	–	7	–	7	7	–
18...	8	8	8	7	6	–	–	–	–	18...	8	7	6	–	5	–	7	7	–
19...	6	8	7	7	6	–	–	–	–	19...	7	8	–	–	6	–	7	7	–
20...	7	8	7	6	4	–	6	8	7	20...	5	6	6	–	6	–	6	6	–
21...	–	–	–	–	–	–	–	–	–	21...	–	8	8	–	6	–	7	–	6
22...	–	7	–	6	5	–	6	7	–	22[1] ..	–	–	–	6	–	–	–	–	–
23...	–	7	–	6	5	–	6	7	–	23...	–	–	8	–	–	–	–	7	–
24...	–	7	–	–	–	–	–	–	–	24...	–	6	–	–	5	–	–	6	–
25...	–	6	5	4	4	4	5	–	–	25...	8	7	6	–	5	–	6	–	6
26...	–	–	6	5	4	5	6	7	–	26...	–	9	7	–	5	–	7	–	6
27...	–	6	5	4	4	5	6	7	–	27...	8	8	7	–	6	–	7	–	6
28...	7	8	7	–	4	–	–	4	–	28...	–	8	7	6	5	–	7	6	–
29...	–	7	6	–	4	–	8	7	–	29...	–	8	7	–	5	–	–	–	7
30...	–	8	7	6	6	–	–	–	–	30...	–	8	7	–	5	–	–	–	7
31...	–	–	–	–	–	–	–	–	–	31[3] ..	–	3	–	–	–	8	–	6	–

of the heating of the mountain then becomes apparent and the definition deteriorates. The disturbances at the Sun's limb under these conditions do not resemble those seen immediately after sunrise, but have a fluttering appearance, which we are accustomed to speak of as the "heating effect." In the late afternoon the seeing usually improves, but it is rarely very good at midday. This is not a rule without exceptions, however, as we have sometimes recorded nearly perfect definition during the hottest hours of the day.

Everyone who has noted the heated air above the surface of the ground will wonder, in considering the effect of such disturbances upon solar observations, whether these disturbances rise to a great height. A casual observation is sufficient to show that the disturb-

[1] Rain [2] Snow [3] Cloudy [4] Storm.

SEEING

September	Hour of Observation							October	Hour of Observation						
	7	8	9	10-2	3	4	5		7	8	9	10-2	3	4	5
1	8	6	–	5	–	7	7	1	7	6	–	5	–	7	6
2	7	8	6	5	–	7	6	2	8	7	–	5	–	–	–
3	8	6	6	5	–	–	7	3	8	7	6	5	–	7	–
4[3]	8	7	–	–	–	–	6	4[3]	–	–	–	–	–	6	–
5[3]	7	6	–	–	6	–	–	5[5]	8	–	–	–	–	–	–
6	8	7	6	5	–	–	7	6[9]	–	–	–	–	–	–	–
7	8	7	6	5	6	–	–	7[9]	–	–	–	–	–	–	–
8	8	7	–	5	–	7	7	8[9]	–	–	–	–	–	–	–
9	8	7	6	5	6	–	–	9[9]	–	–	–	–	–	–	–
10	8	–	6	5	–	7	6	10[9]	–	–	–	–	–	6	–
11	7	7	6	5	–	7	7	11[5]	7	6	–	–	–	–	–
12[3]	8	7	–	–	–	–	–	12	7	8	7	5	–	6	–
13	8	6	–	5	5	–	–	13	6	8	6	6	–	6	–
14	7	6	–	5	–	–	4	14	7	8	7	6	–	7	–
15	8	7	–	5	–	–	6	15	7	7	–	5	–	6	–
16	7	6	–	5	–	7	6	16	6	7	–	6	–	–	–
17[3]	7	6	–	–	–	–	–	17	6	6	–	5	–	6	–
18[5]	7	6	–	–	–	–	–	18	6	6	–	6	–	6	–
19	7	7	–	5	–	–	7	19	6	7	–	6	–	6	–
20[3]	7	6	–	–	–	–	–	20[6]	3	–	6	5	–	–	5
21[3]	–	–	–	–	–	–	–	21	6	6	–	5	–	6	–
22[9]	–	–	–	–	–	–	–	22	7	8	7	5	–	6	–
23[9]	–	–	–	–	–	–	–	23	7	7	7	5	–	6	–
24[9]	–	–	–	–	–	–	–	24	8	8	–	6	7	6	–
25[9]	–	–	–	–	–	–	–	25	7	8	–	6	6	8	–
26[9]	–	–	–	–	–	–	–	26	7	8	–	6	6	–	–
27	–	–	–	–	–	–	–	27	6	7	–	5	6	–	–
28	–	–	–	–	–	–	–	28	6	8	–	5	–	–	–
29	7	–	6	5	–	7	–	29	8	8	6	5	–	–	–
30	7	6	–	5	–	6	–	30[3]	–	–	5	5	8	7	–
								31	8	7	–	5	7	–	–

ance decreases rapidly in passing upward from the ground, but it is, of course, quite impossible to determine by means of the unaided eye the probable effect of this disturbance on telescopic observations. We have accordingly made many observations of the Sun with the 3¼-inch telescope supported in a pine tree at heights above the ground ranging from 20 to 80 feet. The results of these observations clearly indicate that a telescope employed in solar work should be mounted as high above the ground as circumstances warrant. At the lower elevations in the tree the advantage over positions still nearer to the ground was sometimes not appreciable; but at a height of 80 feet above the ground the improvement in definition was very distinct. Probably

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[3] Cloudy. [5] Fog. [6] High wind. [9] Fog and rain.

SEEING

November	Hour of Observation							December	Hour of Observation						
	7	8	9	10-2	3	4	5		7	8	9	10-2	3	4	5
1[3]	–	–	–	6	6	6	–	1[5]	–	–	–	–	–	–	–
2[3]	5	–	–	–	6	–	–	2[5]	–	–	–	–	–	–	–
3	6	6	–	5	6	–	–	3[7]	6	–	–	–	–	–	–
4[3]	8	7	–	5	–	–	–	4[3]	–	–	–	–	–	–	–
5	7	7	–	5	–	–	–	5[8]	–	5	–	–	–	–	–
6	–	8	7	5	6	–	–	6	5	6	–	5	5	–	–
7	7	7	–	6	6	–	–	7	–	6	–	6	6	–	–
8	7	–	–	5	6	–	–	8	–	6	–	5	6	–	–
9	6	–	–	5	6	–	–	9	–	7	–	6	6	–	–
10	5	6	–	5	5	–	–	10	–	–	–	–	–	–	–
11	6	8	–	5	5	–	–	11	–	–	–	–	–	–	–
12[3]	–	–	–	–	–	–	–	12	–	–	–	–	–	–	–
13[3]	–	–	–	–	6	–	–	13	–	6	6	5	6	–	–
14	6	6	–	5	–	–	–	14	–	7	–	5	6	5	–
15	–	–	–	–	6	–	–	15	–	6	–	5	5	–	–
16	7	7	–	5	6	–	–	16	–	8	7	6	6	–	–
17	8	7	–	6	6	–	–	17	–	8	–	6	6	–	–
18	7	7	–	5	6	–	–	18	–	8	–	6	7	–	–
19	7	8	–	6	–	–	–	19	–	8	7	5	6	–	–
20	–	7	6	6	6	–	–	20[3]	–	7	–	–	–	–	–
21	7	7	–	6	–	–	–	21[3]	–	–	–	–	–	–	–
22	7	8	–	6	7	–	–	22[9]	–	–	–	–	–	–	–
23	7	7	–	6	7	–	–	23[9]	–	–	–	–	–	–	–
24	–	–	–	–	–	–	–	24[9]	–	–	–	–	–	–	–
25	–	–	–	–	–	–	–	25	–	–	6	–	6	–	–
26	6	7	–	5	–	–	–	26	–	–	–	–	–	–	–
27[3]	–	–	–	5	6	–	–	27	–	–	–	–	–	–	–
28	7	7	–	5	7	–	–	28	–	7	6	5	6	–	–
29	7	7	7	6	5	–	–	29	–	8	7	6	6	–	–
30[3]	–	6	–	–	–	–	–	30[3]	–	–	7	–	–	–	–
								31[9]	–	–	–	–	–	–	–

this is one of the reasons why the solar definition with the 40-inch Yerkes telescope averages considerably better than we expected it would, for with this telescope the object-glass is over 70 feet above the ground.

OBSERVATIONS WITH THE FIFTEEN-INCH CŒLOSTAT TELESCOPE

In March 1904 a cœlostat of 15 inches aperture was sent to Mount Wilson from the Yerkes Observatory. This instrument had previously been employed by Professors Barnard and Ritchey, of the Yerkes Observatory party, at the solar eclipse of May 28, 1900, in Wadesboro, N. C., and by Professor Barnard at the Sumatra eclipse

[3] Cloudy. [5] Fog. [7] Partly cloudy. [8] Cold and windy. [9] Fog and rain.

in 1901. As used at Mount Wilson, it is supplied with a second plane mirror, mounted south of the cœlostat, and arranged to slide on a north-and-south track in such a way as to receive the solar rays corresponding to any declination of the Sun.

The rays are reflected from this mirror toward the north to a 6-inch photographic objective of 61½ feet focal length, mounted on the extension of the stone pier just above the cœlostat. After passing through this lens the rays traverse a long tube built of wooden framework and covered with paper. The solar image is formed within a small house which terminates this tube at its north end. In the house a photographic plate-holder is mounted, in conjunction with a slide containing a narrow slit, which can be shot at high speed across the solar image by means of a spring. In this way the very short exposure required for direct photography of the Sun can be obtained.

One of the chief points of interest connected with this instrument is the effect of the heating of the air within the tube upon the definition of the solar image. In the first experiments with this apparatus, the skeleton tube was covered on all sides with tar-paper, just as it had been used in the eclipse work. Above the tube, and separated from it by a considerable air-space, was a canvas fly for the purpose of shielding the tube from the direct rays of the Sun. It was found that in the early morning, before the tube had become heated, the definition of the solar image was excellent. In a short time, however, heated air within the tube completely spoiled the definition, and the Sun's image became so blurred and indistinct that no observations of value could be made with it. These circumstances led us to question what the effect would be if no tube were employed. The 6-inch lens was therefore mounted in such a position as to throw the beam horizontally through the air toward the north, outside of the tube and over that portion of the ground which was in shadow. The image observed under these circumstances was found to be much better defined than that seen through the heated air of the tube. We accordingly decided to try the experiment of taking off all of the paper on the two sides which formed the upper half of the tube. It also seemed advisable to stretch the canvas fly at a much greater distance from the tube and to provide means of exit at the top for any heated air which might be found under the fly. As soon as the tube and fly had been re-arranged in this manner, a great improvement was immediately noticed. The definition of the image became much better and the deterioration observed in the previous instance was no longer seen. The air in the tube remained cool, whereas before it had become greatly heated.

These experiments would seem to throw some light on the question of designing suitable tubes and shelters for telescopes used in a horizontal, or nearly horizontal, position. It seems likely that if the cœlostat and the instruments used with it could be mounted on piers at a height of 70 feet or more above the ground, it would be unnecessary to use any tube, particularly if the ground below the path of the beam were shielded from the Sun by a light canvas cover, stretched at a height of several feet above the surface and suitably ventilated. Of course, the practical difficulties in such a construction are very considerable, on account of the great cost and the lack of stability of high piers. For the Snow telescope it therefore seemed advisable to design a special form of house, in the hope of securing good definition with a solar beam at a moderate height above the ground. Experiments made with the 15-inch cœlostat seem to show that this latter instrument is too near the ground for the best results, although it gives excellent definition in the early morning, before the heating of the soil is very great.

The design of the house now under construction for the Snow telescope will be described in a subsequent report. It may be said here, however, that it consists of a skeleton frame of light steel construction, provided with a ventilated roof. The floor is to be of canvas, tightly stretched at a height of one foot above the ground and permitting a free circulation of air below. The inner walls of the house (which is 10 feet wide at its narrowest point) are to be of light canvas, so arranged that they can be raised or lowered at will. The outer walls of the house are to be covered by canvas louvres, so arranged as to shield the entire house from the direct rays of the Sun, and permitting a free circulation of air. The stone pier, 27 feet high, on which the cœlostat will stand, is also to be shielded from the Sun by canvas louvres. The ground surrounding the instrument is fairly well covered with bushes, and the few bare spots can be covered with stretched canvas, if necessary.

Spectroscopic observations.—The spectroscope used with the cœlostat telescope is of the Littrow form: a single lens, of 4 inches aperture and 18 feet focal length, serves at once as collimator and camera lens. After passing through the slit, which is mounted in the focal plane of the photographic objective employed with the cœlostat, the rays pass to the 4-inch objective, by which they are rendered parallel. They then meet the 4-inch Rowland plane grating, having 14,438 lines to the inch, from which they are returned through the 4-inch objective. The image of the spectrum is formed on a photographic plate, mounted in the focal plane and a little to one side of the slit. This apparatus is giving excellent definition, surpassing that of any spectroscope employed at the Yerkes Observatory.

The character of the results obtained with this spectroscope, and its convenience of manipulation, illustrate one of the arguments in favor of fixed telescopes of the cœlostat type, as contrasted with moving equatorial telescopes. At the Yerkes Observatory it has never been possible to attach a sufficiently long and powerful spectroscope to the moving tube of the 40-inch refractor. Such a spectroscope must be mounted in a fixed position on substantial piers, and the telescope must be so constructed as to permit a sharp and well-defined image of the Sun to be maintained in a fixed position on the slit. This can readily be accomplished with the aid of a cœlostat, provided only that the difficulties peculiar to this type of telescope can be overcome. From the experiments so far made, we believe that the difficulties can be surmounted and that the fixed telescope is certain to become an instrument of great importance in the future.

CONCLUSION

From the observations given in this paper, it appears that Mount Wilson meets in a very remarkable degree the requirements of a site for a solar observatory. Indeed, I know of no other site that compares at all favorably with it. If a large solar observatory were established there, it might be expected to yield many important results, not to be obtained under less favorable conditions.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 2

THE SOLAR OBSERVATORY OF THE CARNEGIE INSTITUTION OF WASHINGTON

By GEORGE E. HALE, Director

In a report entitled "A Study of the Conditions for Solar Research at Mt. Wilson, California"[1] I have outlined the circumstances that have resulted in the establishment of a Solar Observatory on Mount Wilson[2] by the Carnegie Institution of Washington. At the recent annual meeting of the board of trustees, a grant of $150,000 was authorized, for use during 1905. It is expected that the first equipment will cost about twice this sum, and that important additions will result in the future from the operation of a large and well-appointed instrument and optical shop.

In April 1904 a grant of $10,000 was made by the executive committee of the Carnegie Institution for the purpose of bringing the Snow telescope to Mount Wilson from the Yerkes Observatory. An expedition for solar research was accordingly organized under the joint auspices of the University of Chicago and the Carnegie Institution, with the understanding that the funds granted by the Carnegie Institution would be used for the construction of piers and buildings, and for other expenses incidental to the work, while the University of Chicago would furnish the instrumental equipment, and pay the salaries of some of the members of the party. Messrs. Ritchey, Ellerman, and Adams, of the staff of the Yerkes Observatory, were to be associated with me in the work. While the executive committee of the Carnegie Institution indicated its intention of supplying further funds, if possible, for use during 1905, it was not supposed in April that provision could be made at present for the establishment of a large and fully equipped solar observatory. Nevertheless, it was agreed with the University of Chicago that if at any time the Carnegie Institution should decide to establish a solar observatory of its own, such an observatory would take the place of the Mount Wilson Station of the Yerkes Observatory, and the work of the Station would be continued under the sole auspices of the Carnegie Institution.

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[1] See *Contributions from the Solar Observatory of the Carnegie Institution* No. 1; *Astrophysical Journal*, March 1905.

[2] The approximate geographical position of the Solar Observatory, as given (by triangulation) by the U. S. Coast and Geodetic Survey, is as follows:

Latitude, 34° 13′ 26″
Longitude, 118° 3′ 40″.

AIM OF THE SOLAR OBSERVATORY

It has been my privilege to outline the plan of research and to determine the equipment of two other observatories. The Kenwood Observatory (subsequently merged with the Yerkes Observatory) had for its prime purpose the development of the spectroheliograph, and its use in solar research. The equipment was consequently designed with this purpose in view. The Yerkes Observatory had its origin in the gift of a 40-inch refracting telescope to the University of Chicago by Mr. Charles T. Yerkes. In designing the Observatory building, and in preparing a plan of research, I felt that the obligation of securing the greatest possible return from this powerful telescope must be a paramount consideration. In the nature of the case, a thoroughly homogeneous scheme of investigation could hardly be adopted for the Observatory under these circumstances, since the lines of work for which the 40-inch telescope is peculiarly fitted are very diverse in character.[1] The various applications of the Yerkes telescope in micrometric observations by Professors Burnham and Barnard; in stellar spectroscopy by Professor Frost and Mr. Adams, and by Mr. Ellerman and myself; in lunar, nebular, and stellar photography by Professor Ritchey; in the photographic study of stellar parallaxes by Dr. Schlesinger; in stellar photometry by Mr. Parkhurst; and in solar research with the spectroheliograph by Mr. Ellerman, Mr. Fox, and myself, will suffice to indicate that a serious attempt has been made at the Yerkes Observatory to realize the full possibilities of this magnificent instrument. But while recognizing the special demands of the 40-inch telescope, I have constantly kept in mind the development of other departments of the Observatory's work. Without enumerating these,[2] I shall confine my remarks to a line of effort which is of importance in the present connection, since it has defined the chief elements in the plan of research of the new Solar Observatory.

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[1] See "The Aim of the Yerkes Observatory," an address delivered at the formal inauguration of the work in 1897. *Astrophysical Journal*, **6,** 310, 1897.

[2] The results accomplished are epitomized in the *Reports of the Director.*

Both in the Kenwood and the Yerkes Observatories the instrument shop was regarded as of great importance, since it alone rendered possible the construction and frequent improvement of instruments of new type or special design. The Rumford spectroheliograph, the Bruce spectrograph, the two-foot reflecting telescope, and the Snow telescope are among the products of this shop. The operations of the shop were not confined to the construction of the mechanical parts of instruments; provision was also made for optical work on a large scale, under the direction of Professor G. W. Ritchey, who also succeeded Professor F. L. O. Wadsworth in the direction of the mechanical work.

In 1896, recognizing the great possibilities of the reflecting telescope for astrophysical research,[1] I engaged Professor Ritchey for the purpose of constructing a mirror of five feet aperture. An account of the methods employed in the grinding of this mirror has recently been given by Professor Ritchey.[2] My father's hope that he might be able to provide a suitable mounting for the five-foot mirror was frustrated by his death in 1898. At that time the fine grinding of the spherical surface had been completed, and the demands of other optical work rendered it advisable to discontinue further operations until funds for a mounting could be obtained. Many attempts were made to secure these funds, but they all proved ineffectual. Meanwhile, the success achieved by Keeler and Perrine with the three-foot Crossley reflector, and the remarkable results obtained by Ritchey with the two-foot reflector of the Yerkes Observatory, directed renewed attention to the possibilities of reflecting telescopes. It soon became clear that a five-foot mirror, if properly mounted, would give results entirely beyond the reach of existing instruments. The committee of the Carnegie Institution on the projects for southern and solar observatories accordingly felt that such a telescope should be included in the Solar Observatory equipment. The figuring and mounting of the five-foot mirror will therefore be undertaken as soon as possible.

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[1] "On the Comparative Value of Reflecting and Refracting Telescopes for Astrophysical Investigations," *Astrophysical Journal*, **5**, 119, 1897.

[2] *Smithsonian Contributions to Knowledge*, Vol. XXXIV.

It is a fortunate circumstance that the construction and use of a great reflecting telescope is a logical element in the general plan of research laid down for the Solar Observatory. In *Year Book* No. 2,[1] of the Carnegie Institution may be found a report on this subject, prepared at the request of Professors Boss and Campbell, my colleagues on the committee, and improved in many particulars as the result of their criticisms. The prime object of the Solar Observatory is to apply new instruments and methods of research in a study of the physical elements of the problem of stellar evolution. Since the Sun is the only star near enough the Earth to permit its phenomena to be studied in detail, special attention will be devoted to solar physics. It is hoped that the knowledge of solar phenomena thus gained will assist to explain certain stellar phenomena. Conversely, the knowledge of nebular and stellar conditions to be obtained through spectroscopic and photographic investigations with the five-foot reflector should throw light on the past and future condition of the Sun. All of the principal researches will thus be made to converge on the problem of stellar development. The name "Solar Observatory" is regarded as appropriate, since the spectroscopic study of stars and nebulæ, to be carried on in connection with the solar work, are essential elements in any attempt to determine the mode of origin, the development, and the decay of the Sun as a typical star.

How, then, shall we attack in an effective manner the complex problem of stellar evolution? It goes without saying that I can offer no general answer to this question; I can only point out the three principal lines of attack which we hope to pursue at the Solar Observatory. These involve:

1. The more complete realization of laboratory conditions in astrophysical research, through the employment of fixed telescopes of the cœlostat type, and through the adoption of a *coudé* mounting for the five-foot reflector. This should permit: (*a*) the use of mirrors or objectives of great focal length, thus providing a large image of the Sun for study with spectroscopes and spectroheliographs; (*b*) the use of long focus grating spectroscopes, mounted in a fixed position in constant temperature laboratories, for the photography of stellar spectra requiring very long exposures; (*c*) the use of various labora-

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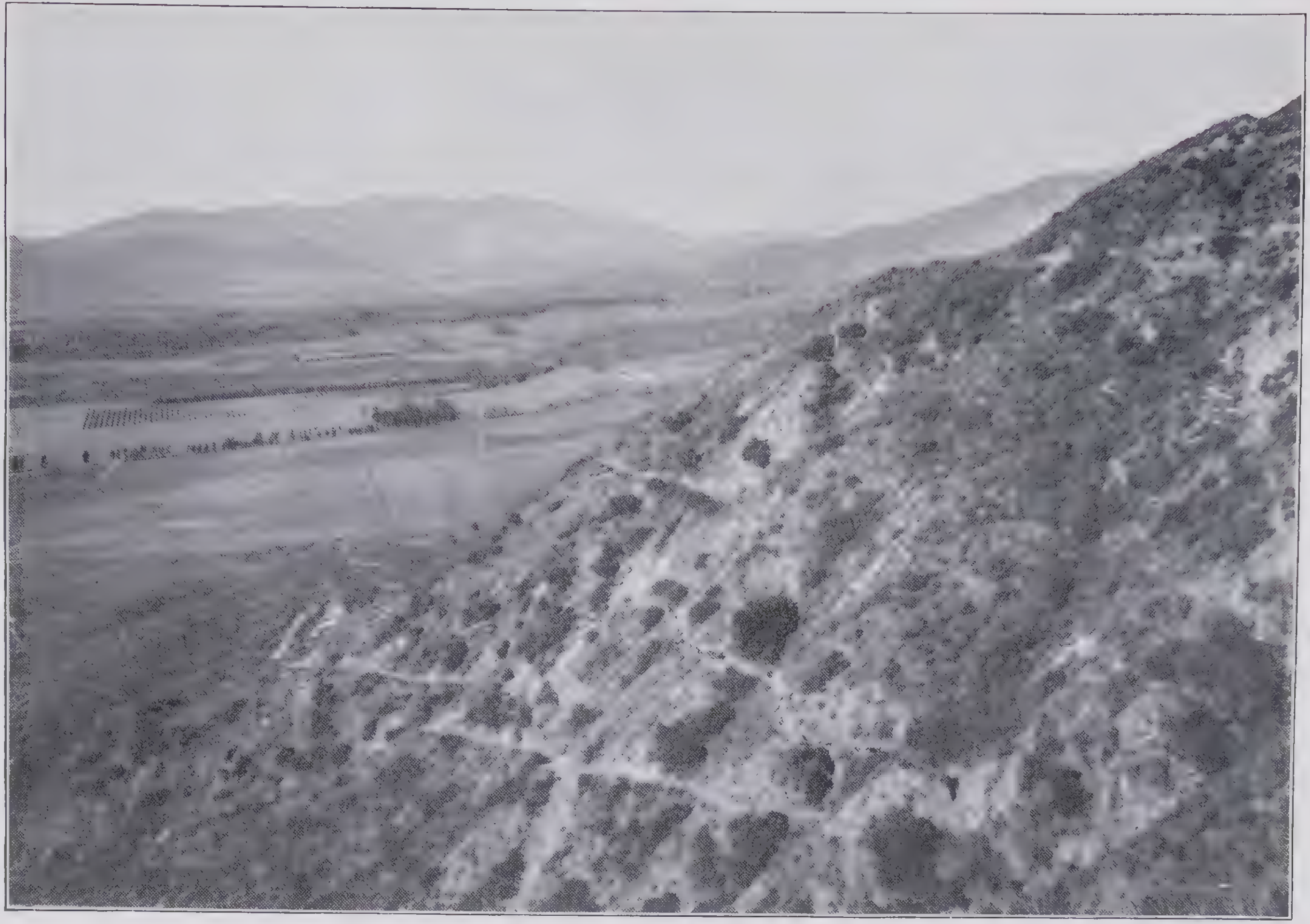
[1] Page 49.

PLATE VIII.



Lower Part of Mount Wilson Trail, Showing Pack Animals Loaded with Lumber

tory instruments, such as the radiometer, which cannot be employed in conjunction with moving telescopes.

2. The development of the spectroheliograph in the various directions suggested by recent work at the Yerkes Observatory, including the photography of the entire solar disk with dark lines of hydrogen, iron, and other elements; further application of the method of photographing sections of flocculi corresponding to different levels; special studies of sun-spots, etc.; and daily routine records of calcium and hydrogen flocculi and prominences.

3. The construction of a five-foot equatorial reflector, with *coudé* mounting, and its use in the photography of nebulæ, the study of stellar and nebular spectra, and the measurement of the heat radiation of the brighter stars.

It was originally intended that a prolonged series of determinations of the solar constant, extending over at least one sun-spot period, should be made an important feature of the Observatory's work. The plans outlined in *Year Book* No. 2 accordingly included an equipment at Mount Wilson for this purpose, and suggested, in harmony with Dr. Langley's view, that provision be made for two additional stations, one near the summit of a high mountain, at an elevation of about 12,000 feet, the other at a much lower level on the same mountain. The principal purpose of these two stations was to measure the atmospheric absorption, in order to eliminate it from the solar constant determinations. The recent developments of Dr. Langley's researches at Washington have led Mr. Abbot, who is associated with Dr. Langley in the work, to the conclusion that entirely satisfactory results can be obtained there by the method employed. The poor atmospheric conditions with which the Washington observers have so successfully contended, and the disturbances arising from ground tremors in the heart of a large city, would be largely eliminated at Mount Wilson. For this reason it seems probable that results of higher precision could be obtained at this site. I have accordingly offered Dr. Langley facilities for pursuing the investigation at Mount Wilson, which I trust he may find it possible to accept.

In addition to the above-mentioned observations, provision will be made at Mount Wilson for various laboratory investigations necessary in conjunction with solar research. In view of the importance of securing a complete record of solar phenomena when magnetic storms are in progress, suitable magnetic apparatus, recommended by Dr. L. A. Bauer, in charge of the Department of Terrestrial Magnetism of the Carnegie Institution, will be installed at a sufficient distance from the electrical machinery.

TRANSPORTATION OF MATERIAL

The first problem that confronts one in undertaking the construction of buildings and the erection of instruments on Mount Wilson is that of transportation over the trail from the valley. Two trails are available—the "Old Trail," from Sierra Madre, and the "New Trail," from the foot of Eaton Cañon, six and one-half miles from Pasadena. The New Trail, which is much the better of the two, is about nine miles long. At its narrowest points it is little over two feet in width, and in some of these places it had to be widened before the transportation of the heavy parts of the Snow telescope could be attempted. For ordinary packing with "burros" (donkeys) or mules the trail is well adapted. The loads brought up in this way range from 80 to 225 pounds per animal, and the charges from $1 to $1.35 per hundred pounds. On account of the expense of transportation over the trail, the best cement costs on the mountain more than twice as much as in the valley.

With a single exception, all parts of the 15-inch cœlostat, which was erected on Mount Wilson in April 1904,[1] were brought up on animals. The equatorial head of this instrument, which weighs about four hundred pounds, is too heavy to be carried in this way. A carriage was accordingly improvised for it from a two-wheel truck, such as is used by the railway companies for trunks. This served the purpose fairly well, though two days were required for the trip up the mountain. It was evident that a different arrangement would be required for heavier castings.

After provision had been made for the use of the Snow telescope on Mount Wilson, the carriage shown in Plate IX was designed. The running gear consists of four automobile wheels, 28 inches (71 cm) in diameter, with $2\frac{1}{2}$ inch (6.3 cm) rubber tires. The distance between the

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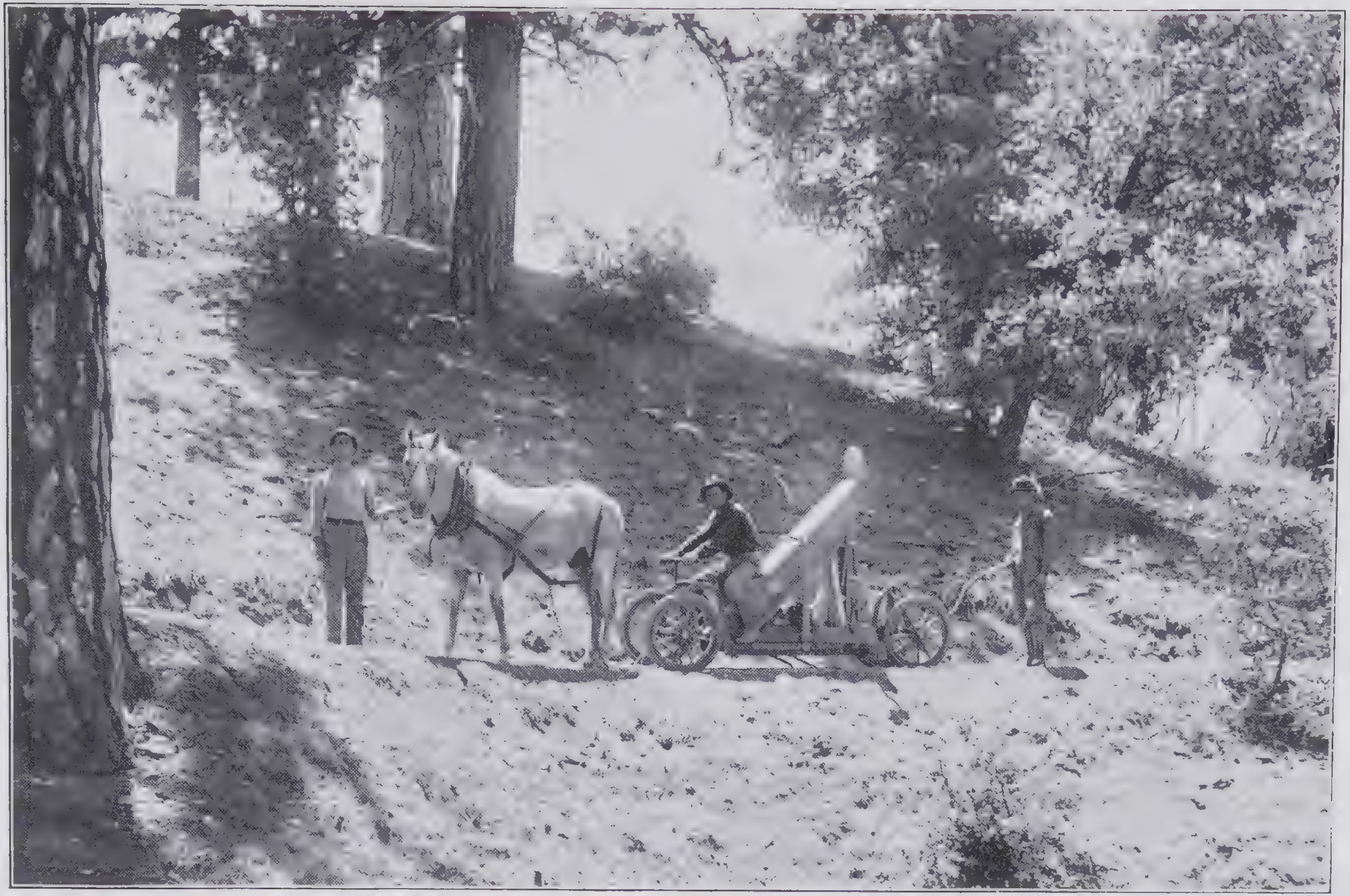
[1] See *Contributions from the Solar Observatory*, No. 1, *Astrophysical Journal*, March 1905.

PLATE IX



Truck for Hauling Heavy Instruments on Mount Wilson Trail

wheels was limited by the width of the trail to 24 inches (61 cm). The bed of the truck is hung by wrought-iron yokes from the running gear, the lower surface of the bed being at a height of 6 inches (15 cm) above the ground. Steering gear, of the type used on automobiles, is provided for both pairs of wheels. A man riding on the load steers the forward wheels with a hand wheel, while the rear wheels are steered with a tiller by a man walking behind the carriage. A single large horse pulls a load of a thousand pounds on this carriage without difficulty. With two horses, used in relays, the trip from the lower end of the trail to the summit and return (a total distance of about nineteen miles) is completed with such a load in less than two days (about fifteen hours on the trail). With loads not exceeding 700 pounds the round trip is completed in a single day. Up to the present time the truck has made fifty round trips, carrying all the mirrors, lenses, and heavy castings of the Snow and Bruce telescopes, the parts of a fifteen horse-power gas engine, and other heavy machines, as well as the four-inch pipe columns (some of them twelve feet long) used in constructing the steel skeleton of the telescope house (Plate XI). The lighter angle-iron and other parts of the telescope house were brought up on burros. The total weight of material carried over the trail for the present work amounts so far to about 175 tons.

As the steering and control of the carriage on the narrow mountain trail is a difficult and dangerous task, special mention should be made of the excellent work of Mr. C. O. Sparks, who has been in charge of the carriage on all of its trips. It is to the credit of Mr. Sparks that nothing has been lost or injured during transportation.

Before the heavy castings (some of them weighing as much as five tons) required for the mounting of the five-foot reflector can be taken up Mount Wilson, the trail must be widened or some other mode of transportation provided.

THE SNOW TELESCOPE

As no description of this instrument has been published, the present brief account may be prefaced by a statement regarding the construction of the telescope.

In designing the Yerkes Observatory in 1894, I provided a large heliostat room, 12 feet (3.66 m) wide and 104 feet (31.7 m) in length.[1] A small heliostat loaned by Professor Keeler was used in this room in 1897, and it was intended to mount permanently there, mainly for spectroscopic work, a combined heliostat and cœlostat designed by Professor Wadsworth.[2] When employed as a cœlostat, a second fixed mirorr was to be used with the instrument, so as to give the desired direction to the reflected beam.[2] Some of the patterns for this instrument were made, but the pressure of other work made it necessary to postpone the construction for some time.

In 1900, after Professor Ritchey had succeeded Professor Wadsworth as superintendent of instrument construction, a cœlostat with mirror of 15 inches (38 cm) aperture was made, from Professor Ritchey's designs, for the total solar eclipse of that year. This gave such satisfactory results that the plan of constructing a large cœlostat was again taken up. Unfortunately, however, no funds were available for this purpose. In 1901, during a visit to the Observatory of Professor Cross, chairman of the Rumford Committee, I showed him the details of the instrument, as worked out by Professor Ritchey. The design called for a cœlostat of 30 inches (76 cm) aperture, with second plane mirror of 24 inches (61 cm) aperture, the latter mounted so as to slide northeast and southwest on rails lying east of the cœlostat. The concave mirror, to which the light was reflected from the second plane mirror, had a focal length of 61 feet, and a second concave mirror, of 165 feet (50.3 m) focal length, was also to be used. For this reason the heliostat room, 104 feet (31.7 m) in length, was not long enough for our purpose, and the position of its axis, in the meridian, involved loss of light. It was accordingly necessary to erect a long wooden building, on the ground south of the Yerkes Observatory.

At the kind suggestion of Professor Cross, a grant of $500 was made by the Rumford Committee in aid of an investigation to be undertaken with this telescope. Subsequently, through the kindness of Professor Pickering, chairman of the Draper Committee, two other grants, of $500 each, became available. With these funds, helped out by small amounts obtained from other sources, the work was begun.

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[1] See "The Yerkes Observatory of the University of Chicago," Part II, *Astrophysical Journal*, **5**, 260, 1897.

[2] *Ibid.*, p. 261.

An account will be published later of this cœlostat and its accessory apparatus. The long wooden house on the Observatory grounds which contained it was destroyed by fire on December 22, 1902, through the breaking down of the insulation of a high-voltage electric transmission line, which supplied the spark used for a comparison spectrum. A 24-inch plane mirror and some of the mirror supports were saved, but most of the apparatus was completely destroyed or rendered useless.

Confident that the necessary funds could be obtained from some source, I decided to construct at once a new and better instrument, and to provide for it a more suitable house. Two important changes were made in the design. In the tests of the telescope, made by Mr. Adams and myself, the definition was poor, both in the case of the Sun and the stars. I attributed this in part to the fact that the cœlostat was mounted on a pier, the surface of which was only a few inches from the ground. This led me to observe distant objects at various heights above the ground with the naked eve, with field glasses and small telescopes, and finally with the 12-inch refractor, which stands on a pier about 40 feet (12.2 m) high. I soon reached the conclusion that the cœlostat must be mounted as far as possible above the ground, and that a site shaded by low trees or bushes would be much better than unshaded soil.

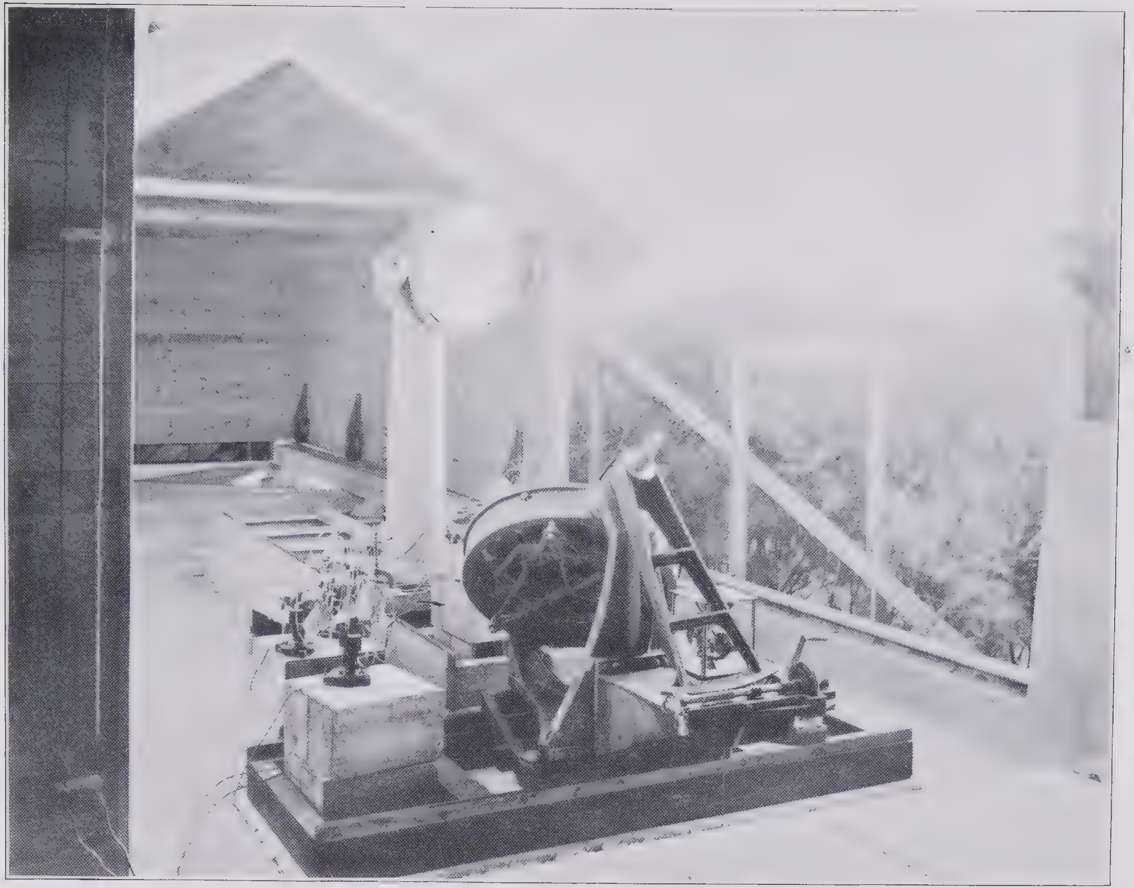
A gift of $10,000 from Miss Helen Snow, of Chicago, in memory of her father, the late George W. Snow, provided sufficient funds to complete the telescope and to instal it in a suitable house. The cœlostat was mounted on a brick pier, at a height of 15 feet (4.57 m) above the ground. In Professor Ritchey's design of the previous instrument the rays were reflected in a northeasterly direction from the cœlostat mirror to a second plane mirror, which sent them toward the southwest to one or the other of the concave mirrors. In designing the Snow telescope, a new arrangement of the second mirror was adopted by Professor Ritchey, at the suggestion of Mr. C. G. Abbot. As Plate X indicates, the light is reflected upward and to the south from the cœlostat mirror to a second plane mirror, mounted in a fork at the upper extremity of an iron column, on a carriage which can be moved along heavy iron rails. The position of this carriage on the rails depends upon the declination of the observed object: with a low Sun the second mirror stands close to the cœlostat, but with a high Sun it must be moved away in order to intercept the reflected beam. The cœlostat itself may be moved east or west on its own rails, so that a low object near the meridian may not be hidden by the second mirror or its support.

With the exception of the solar and stellar spectroscopes, for which suitable gratings could not be obtained, the Snow telescope was practically completed in the autumn of 1903. On October 3 of that year it was formally presented to the University of Chicago by Miss Snow, in the presence of a number of guests. Dr. George S. Isham, on behalf of Miss Snow, made the presentation address. The address of acceptance was made by Dean R. S. Salisbury, of the Ogden Graduate School of Science. The manner of using the telescope was afterward demonstrated.

The tests of the telescope made at this time seemed to indicate a decided improvement in definition, which I attributed to the greater elevation of the cœlostat. The Sun's image was frequently well defined, in spite of the change of focus due to the heating of the mirrors. Of this change more will be said later. At present I wish to refer especially to the definition as affected by the design of the telescope house.

The parallel beam from the second mirror was reflected due north through a spectroscopic laboratory into a long, narrow room, at the end of which the concave mirror stood on a massive brick pier. After striking the mirror, the beam was reflected back, so as to form an image of the Sun or a star in the spectroscopic laboratory a short distance from the axis of the parallel beam. The walls and floor of the house are of wood, and the question arises whether their radiation may not heat the air in the house, and thereby affect the definition. In general, the temperature of the air within such a house must differ in some degree from that of the air outside. Hence, some effect on the definition might be expected. The warm air rising about the cœlostat, due in part to the heating of the wooden walls which surround the pier, may also cause some disturbance of the image.

PLATE X



The Snow Telescope when Mounted at the Yerkes Observatory

Rayleigh has shown that in a telescope tube only 12 cm long, a stratum of air in the upper part of the tube, occupying only a moderate fraction of the entire volume, would produce a sensible effect on the definition if heated 1° C.[1] In a tube 60 feet (18.3 m) long, through which the beam passes twice, the difference in temperature of a stratum, required to produce a similar effect, would be only about one three-hundredth of a degree. The assumed retardation is one-quarter of a wave, and the change of temperature from one side of the beam to the other is supposed not to be uniform.

To the practical observer such a result may seem to have little meaning. I have repeatedly seen the solar image beautifully defined with the 40-inch (102 cm) Yerkes refractor, when the air within the tube had become greatly heated—and certainly not uniformly so—after hours of continuous observation. Indeed, it is difficult to understand how such excellent definition can be obtained under these conditions. For in the optical testing-room Rayleigh's conclusions are easily verified. The great difficulty of securing a satisfactory test of a mirror by the Foucault test is well known; with a focal length as great as 145 feet (44.2 m) our opticians have waited for weeks to obtain a satisfactory test, even in the quiet air of the long testing-room in the basement of the Yerkes Observatory. The trouble resulting from stratification of the air, and the disturbance caused by the proximity to the beam of a person's hand, are familiar to all opticians. With these difficulties in mind, the problem of obtaining really good images of the Sun appears very serious. Yet the fact remains that good images are sometimes obtained. The great height of the 40-inch objective above the ground is probably an important advantage of this telescope, though the radiation of the dome on each side of the shutter-opening must produce some disturbance. The mere heating of the cell of the objective by the Sun would seem to be a sufficient cause for serious disturbance of the definition. Of course it is extremely probable that with sufficiently good atmospheric conditions all of these heating effects are actually perceptible in some degree, and that if they could be eliminated the seeing would be much better than it is now. A skeleton tube, with a simple device for shading the cell, would probaply be advantageous.[1]

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[1] *Collected Papers,* Vol. I, p. 434.

During the tests of the Snow telescope at the Yerkes Observatory, Langley's plan of stirring the air along the path of the beam was tried. The beam was made to pass through a tube of thick building paper, supported on a light wooden frame of square section, about 36 inches (91 cm) square. Electric fans were mounted at openings cut in the walls of the tube. When running at high speed, they kept the air within the tube in constant motion. At times the image of the Sun was distinctly improved in definition soon after the fans were started; but in other cases no improvement whatever resulted. It nevertheless seemed probable that a modified method of stirring the air might advantageously be employed for the Snow telescope house on Mount Wilson, and a tentative design was prepared. But further tests, made at my request by Professor Ritchey, indicated that we could not hope for satisfactory results without much more experimenting than we could afford to undertake. I accordingly abandoned this plan, and designed the cœlostat house described below.

CŒLOSTAT HOUSE ON MOUNT WILSON

In designing the new cœlostat house, I was influenced by two principal considerations:

1. The importance of placing the cœlostat as far as possible above the ground, which had been indicated by observations made with a telescope in a tree at elevations ranging from twenty to seventy feet.

2. The importance of constructing the house in such a way as to reduce to a minimum the heating and the radiation of the floor, walls, and ceiling, with the purpose of keeping the air within the house at the same temperature as the outer air.

In plan (Fig. 1), the building resembles the Snow telescope house at Williams Bay. The cœlostat stands on a carriage, which can be moved east or west along the rails, *a a*. On account of the configuration of the ground, which falls rapidly toward the north, it was necessary to make the long axis of the building run fifteen degrees east of north, instead of being exactly in the meridian. For the same reason this axis is not horizontal, but inclines downward five degrees toward the north. Without these modifications of the original plan, the height of the northern part of the building would have been very great, involving serious increase of expense. The rails *b b*, on which the carriage bearing the second mirror slides, are parallel to the optical axis.

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[1] The case of the 40-inch telescope tube is doubtless hardly comparable with that of the Snow telescope house. The 40-inch tube is sealed by the objective at the upper end, and there is little mixture of the heated air of the tube with the cooler air outside. For this reason it would be interesting to close the end of the telescope house (near the cœlostat) with an objective, and try the definition under such conditions, i. e., without the concave mirror.

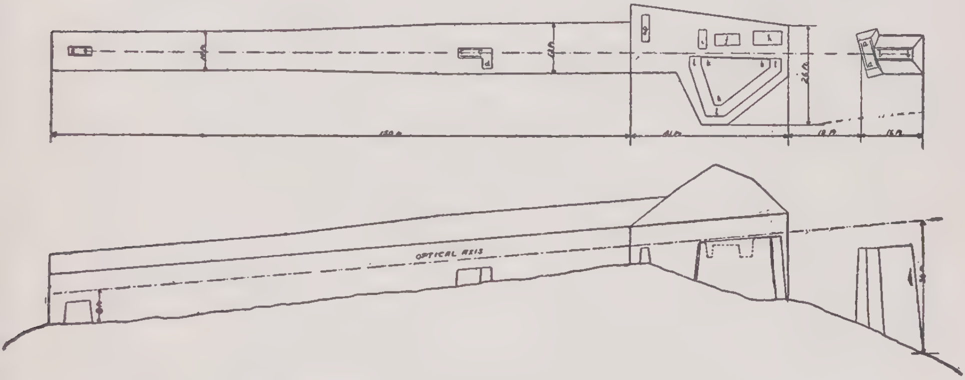


FIG. 1.—Plan and Elevation of Snow Telescope House on Mount Wilson.

Two concave mirrors, each of 24 inches (61 cm) aperture, are to be used. Of these, the mirror of 60 feet (18.3 m) focal length is mounted on its carriage so that it can be moved (for focusing), along the rails *c c*. The mirror of 145 feet (44.2 m) focal length is to be similarly mounted on the rails *e e*. When the long-focus mirror is to be used, the mirror of 60 feet focus is moved to one side, on the extension of its pier at *d*.

In designing the spectroscopic apparatus for the telescope, I have had the benefit of valuable suggestions from all members of the staff. The instruments are to be five in number, as follows:

1. A spectroheliograph with portrait lenses of 8 inches (20.3 cm) aperture, and 60 inches (152 cm) focal length, provided with four dense flint prisms. This instrument is to be carried on the pier *f*, where it will be floated in mercury (to reduce the friction of steel balls

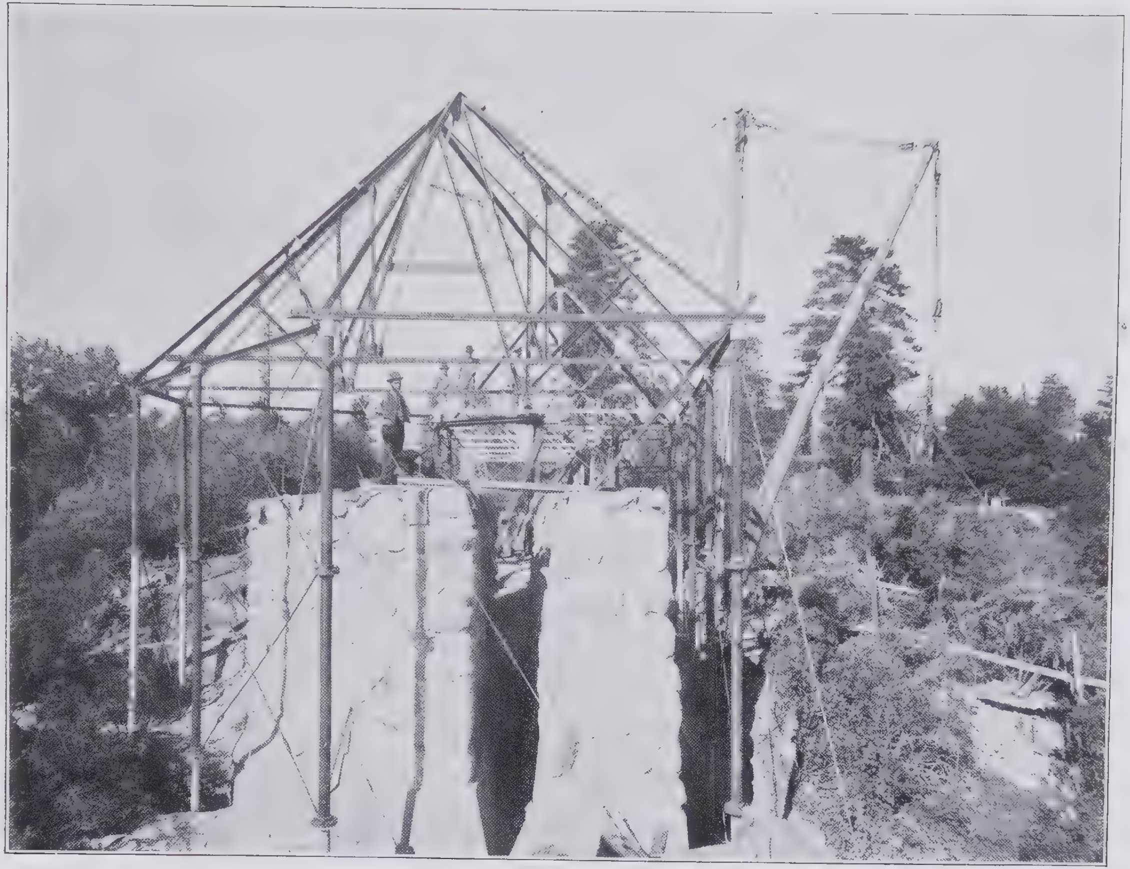
running in V rails), and moved as a whole across the 6.7 inch (17 cm) solar image given by the mirror of 60 feet focal length. The principal purpose of the instrument is to secure daily photographs of the entire solar disk with the calcium and hydrogen lines.

2. A spectroheliograph with lenses of 5 inches (12.7 cm) aperture, and 30 feet (9.14 m) focal length, provided with three light flint prisms of 50° angle. The first and second slits of this spectroheliograph are to stand on the pier *g*, while the collimator and camera lenses and the prism train will be carried by the pier *h*. The spectroheliograph will be fixed in position, and the 16-inch (41 cm) solar image given by the mirror of 145 feet focal length will be moved across the slit by a slow motion of rotation, about a vertical axis, of the 145 foot mirror. At the same time, the photographic plate will be moved synchronously across the second slit. The principal purpose of this instrument is to photograph zones about 4 inches (10 cm) wide of the large solar image, using the lines of iron and other elements which are too narrow to be employed with spectroheliographs of small dispersion. The instrument will also be employed with a plane grating, as a spectroscope for the study of the spectra of sun-spots, etc.

3. A Littrow spectrograph of 18 feet (5.49 m) focal length, with large plane grating. The single objective (on pier *h*), that serves for collimator and camera, will form an image of the spectrum just above the slit (on pier *j*). This spectrograph will be used with the 60-foot mirror, mainly for a study of the solar rotation and the spectra of sun-spots.

4. A concave grating stellar spectrograph, of about 15 feet (4.57 m) equivalent focal length, mounted on the massive pier *k k k* in the constant-temperature room *l l l*. A collimating lens of 5 inches (12.7 cm) aperture will be used with the grating, in order to avoid astigmatism. For the present, until a suitable concave grating can be obtained, a plane grating will be used with a camera lens of 5 inches aperture, and about 13 feet (3.96 m) focal length. This spectrograph is to be employed with the 60-foot mirror in an attempt to photograph, with high dispersion, the spectra of some of the brightest stars. The fixed position of the spectrograph on a massive stone pier, and the possibility of maintaining the grating at a constant temperature, should render very long exposures feasible.

PLATE XI



House for Snow Telescope on Mount Wilson
Looking North from Cœlostat Pier

5. A prism spectrograph, with collimator lens of $1\frac{1}{2}$ inches (3.8 cm) aperture and 45 inches (114.5 cm) focal length, dispersion of from one to four prisms, and camera lenses of various focal lengths, all of ultra-violet glass. The optical parts of the spectrograph will be mounted in such a way that they can be used on the large pier in the constant-temperature room, in conjunction with the slit of the concave grating spectrograph. The prism spectrograph will be used for special studies of stellar spectra, especially in the ultra-violet region.

It is to be understood that instruments 1, 2, and 3 are to be so supported, at different levels, that they will not interfere with one another, and will always be ready for use. The prism spectrograph, however, must be moved to one side when the concave grating spectrograph is to be employed.

The arrangement of the apparatus having thus been explained, let us consider more particularly the construction of the building. As Plates XI and XII show, the structure is of steel, as light as due regard for occasional high winds will permit. Steel guy ropes, anchored to large masses of concrete, afford the additional strength required in the heavy storms of winter. Since the parallel beam from the cœlostat to the concave mirror passes through a closed tube, it is not essential that this part of the building should stand high above the ground. Where the rays of the Sun fall upon the cœlostat itself, however, there can be no protection of the beam, and consequently it is desirable that the cœlostat should stand at a considerable elevation. After many tests of the seeing had been made at various points on the mountain, a site was finally selected which seemed to meet the required conditions. The cœlostat pier stands on a south slope, commanding a practically unobstructed horizon. At its south end this pier rises 29 feet (8.8 m) above the ground; hence, as the center of the second mirror is 74 inches (1.88 m) above the pier, the optical axis of the telescope is at this point about 35 feet (10.7 m) above the ground. At the north end of the pier the rising slope of the hill decreases this height to about 25 feet (7.6 m). When not in use, the cœlostat and second mirror are covered by a house on wheels, closed at both ends by double walls of heavy canvas. These may be opened, so that when the house is moved to the north, the cœlostat stands completely exposed. The movable shelter then fits closely against the south wall of the spectroscopic laboratory, and thus forms a part of the tube through which the beam passes. When in this position the shelter has a canvas floor, so that the beam is completely protected from ascending currents after it leaves the north end of the cœlostat pier.

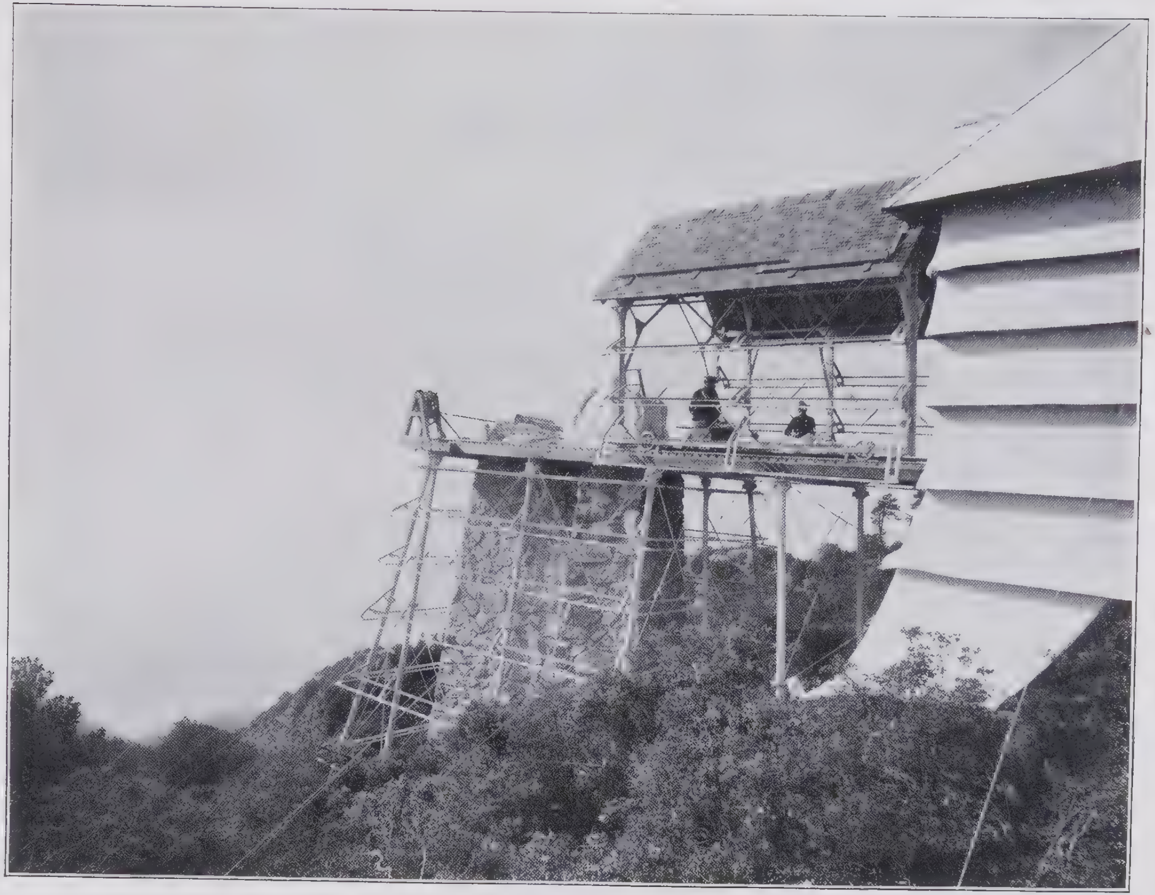
All parts of the building, including the movable shelter, the spectroscopic laboratory, and the long, narrow house extending north from the spectroscopic laboratory, have an inner wall and ceiling of canvas, and an outer wall composed of canvas louvres, very completely ventilated. The roof is also ventilated, by wooden louvres at the ridge, thoughout the entire length of the movable shelter and the north extension, and at the peak of the laboratory. Rain and snow are prevented from entering the roof louvres by means of canvas curtains, which can be raised or lowered at will. The house extending north from the laboratory has a floor of canvas, with an air-space below, through which the air may pass freely.

In traversing the spectroscopic laboratory, the beam necessarily passes very close to the wall of the constant-temperature room. To diminish the effect of radiation from this wall, a covering of sheet metal is arranged so that a constant current of air may be drawn between the sheet metal and the wall by means of an exhaust fan. Outer air is brought in from the west side of the laboratory, and no internal drafts are created, as the connections between the air-space and the supply and exhaust tubes are perfectly tight. It is hoped that any evil effects of radiation from the stone piers and the wooden floor of the spectroscopic laboratory can be eliminated by similar devices.

The louvres surrounding the cœlostat pier are intended to protect the pier from vibration caused by the wind, and from heating by the Sun. The steel structure does not touch the pier at any point, and is therefore made rigid enough to support itself in high winds.

The cœlostat, and the supports for the plane mirror and the 60-foot concave mirror, are now in place on the piers, but heavy storms have prevented the mirrors from being mounted. The concave grating stellar spectrograph is nearly ready to be set up, and work is well advanced on the smaller of the two spectroheliographs. The ultra-violet glass prisms and lenses for the stellar spectrograph have been

PLATE XII



House for Snow Telescope on Mount Wilson
Showing Cœlostat Pier and Movable Shutter

completed by the Carl Zeiss Company, and orders have been placed for the optical parts of the 30-foot spectroheliograph and the Littrow spectrograph. Through the courtesy of the president and trustees of the University of Chicago, the Snow telescope and some of its accessories will be used by the Solar Observatory for some time. It will subsequently be replaced by a similar telescope constructed in our own instrument shop.

THE HOOKER EXPEDITION

As the result of a gift of $1,000, made by Mr. John D. Hooker, of Los Angeles, the Bruce photographic telescope of the Yerkes Observatory has been brought to Mount Wilson by Professor Barnard, for use during a period of several months, after which it will be returned to Williams Bay. A full description of this telescope has recently been published by Professor Barnard in the *Astrophysical Journal.*[1] The house built for the Bruce telescope on Mount Wilson has a sliding roof, which leaves the entire sky free when it is pushed back. Professor Barnard has already obtained some excellent photographs of *Orion* and other constellations. Their quality is such as to give promise of important results, as soon as the stormy weather of the rainy season abates sufficiently to permit long exposures to be given.

THE "MONASTERY"

In the original estimates for the Solar Observatory, made by the committee of the Carnegie Institution, $52,500 was set apart for the construction of dwelling houses on Mount Wilson for the families of the staff, and $51,000 for a large building, containing offices for all the members of the staff, and rooms for laboratories and instrument shops. In these particulars the report simply adopted the plan followed by the Lick and Yerkes Observatories. A residence of six months in a log cabin on Mount Wilson, under conditions which rendered necessary the greatest economy of expenditure, convinced me that a better use could be made of the Institution's funds. In the first place, it is by no means desirable to confine families, and especially children deserving every educational advantage, within the narrow limits of an isolated observatory colony. Furthermore, the work of an instrument shop, and much routine computing as well, can be done at much less expense and to better advantage in a town, where foundries and various sources of supply are at hand, and better workmen and computers can be employed. Finally, a great economy can be effected by using funds for instruments, machinery, and books—the tools of the investigator—that would otherwise be spent for mere buildings. In short, I believe the principle should be recognized that the mountain site is valuable for *observations*, and that most other classes of work can be better done elsewhere. These considerations strike one most forcibly in a place where the cost of building materials is doubled by transportation over the trail.

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[1] **21**, 35–48, 1905.

The isolation of most mountain sites, however, might seem to demand that the staff of such an observatory should be composed only of celibates, or that its members must be content to experience long periods of separation from their families. In this particular Mount Wilson is most fortunately situated. The city of Pasadena, which is hardly to be surpassed as a place of residence, lies at the very foot of the mountain, and can easily be reached in two and one-half hours. Los Angeles, with its large machine shops, foundries, and supply houses, is also near at hand. It is thus perfectly feasible to have the families of the observers live in Pasadena, where members of the staff can spend Sundays, and go on business at other times. We are following this plan, and find it is as satisfactory as could be expected under the circumstances.

I consider it very desirable that each member of an observatory staff, if engaged in work requiring concentrated attention, such as computing or measuring, should have a workroom of his own. The space occupied may be very small, but it should certainly be set apart for individual use. This requirement, together with the necessity of supplying living accommodations for the astronomers, determined the design of the "Monastery."

As shown in plan in Fig. 2, the building has two wings; one containing the dining-room, kitchen, pantries, two bedrooms, woodshed, etc.; the other, the bedrooms and offices of the astronomers, guest-room, bathroom, etc., opening on a long, narrow hall. Each astronomer has a small bedroom and an adjoining office. The convenience of this arrangement, and the satisfaction it has given to all the members of the staff, indicate that a great saving in expense, without loss of efficiency, will be effected. The large room, with stone fireplace, which unites the two wings, serves as a general library. The "Monastery" stands at the extreme end of a narrow point with precipitous walls, and commands a fine view of the neighboring mountains, the San Gabriel Valley, the cities of Pasadena and Los Angeles, and the Pacific Ocean. It was designed, after our plans, by Messrs. Hunt & Gray, architects.

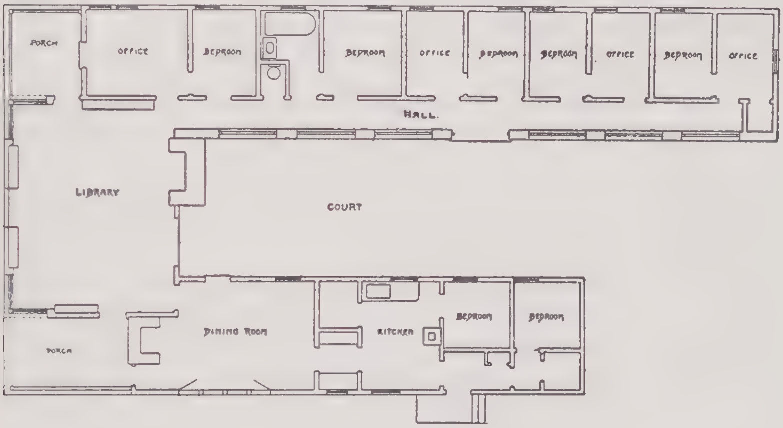

FIG. 2.—Plan of the "Monastery."

Through a recent gift from Mr. John D. Hooker, a small guest-house, containing two bedrooms and a living-room, will soon be erected near the Monastery.

POWER HOUSE AND REPAIR SHOP

A one-story building, 15 × 35 feet (4.57 × 10.67 m), situated between the Snow telescope and the "Monastery," is equipped as a small power-house and repair shop. It contains a 15 horse-power Witte gasoline engine; $7\frac{1}{2}$ K. W. dynamo, giving either alternating or direct current; storage battery of thirty cells, small screw-cutting lathe; Rivett milling machine; sensitive drill; emery grinder; Oliver trimmer; forge and anvil; and a good assortment of small tools needed for repairs and for a certain amount of construction work.

Although our large instrument shop in Pasadena is prepared to undertake any class of work, I regard a small shop on the mountain as indispensable. The engine, dynamo, and storage battery furnish current for arc and spark discharges, and for temperature control required in spectroscopic work, power to run the spectroheliographs, exhaust fan, etc., and light for the offices and laboratories.

A line for transmitting electric power from the San Gabriel Valley will be installed later, since much more power will be required for the 5-foot reflector and other purposes. The present power plant was provided before it was known that a large Solar Observatory would be established by the Carnegie Institution.

It was originally intended to supply water to the various buildings from a well at Strain's Camp, about 325 feet (99 m) below the summit of Mount Wilson; but as the well yielded almost no water last autumn (after an unusually dry period), it is likely that a more reliable source will be chosen.

GENERAL LABORATORY

A small laboratory building, probably of fire-proof construction, will be erected near the Snow telescope in the spring. This will contain a large grating spectrograph, with various accessory apparatus, such as a Du Bois half-ring electromagnet for the Zeeman effect, an arc in pressure chamber, a transformer and condenser for studies of spark discharges, etc. The equipment will also include a Pulfrich stereocomparator, principally for the study of spectroheliograph plates; an Abbe spectrometer; an interferometer, for the measurement of absolute wave-lengths; measuring machines for spectra and for stellar photographs; globe for the measurement of heliographic positions, etc. In addition to the spectroscopic laboratory, the building will contain a small chemical laboratory, an enlarging room, photographic dark-rooms, rooms for the storage of negatives, etc. A visible recording variometer and magnetic storm detector will be established in a separate building, for use in connection with the solar observations.

PASADENA OFFICES AND LABORATORIES

With the invaluable assistance of the Pasadena Board of Trade, a piece of land, on Santa Barbara Street, 150 feet (45.7 m) front by

208 feet (61 m) deep, has been secured for the Pasadena offices and instrument shop. The building, which is now under construction, was designed by Professor Ritchey. It is 50×100 feet (15.2×30.5 m) in size, with an optical testing-room, 150 feet (45.7 m) long, extending 68 feet (20.7 m) beyond it in the rear. The walls are of brick, and the floor of cement. Pains will be taken to make the structure throughout as nearly fire-proof as the available funds will permit, since the optical and mechanical parts of instruments under construction will be very valuable.

The building will contain offices for Professor Ritchey and myself, and a stenographer; drafting-room, machine shop, instrument shop, pattern shop, lacquering-room, constant-temperature room, room for 5-foot (1.5 m) grinding machine, room for 40-inch (1 m) grinding machine, long optical testing-room, photographic dark-rooms, enlarging-room, etc. The equipment includes a No. 2 Brown & Sharpe Universal milling machine, 24×24-inch (61×61 cm) Gray planer, 20-inch (51 cm) Hendey-Norton engine lathe, 12-inch (30.5 cm) Hendey-Norton tool maker's lathe, No. 4 Rivett bench lathe, No. 2 Landis Universal grinding machine, drill press, pattern-maker's lathe, circular saw, band-saw, Oliver trimmer, automatic hack-saw, emery grinder, etc. The supply of small tools is very complete. The optical laboratory will contain all necessary machinery for grinding, polishing, and testing mirrors, with apertures as great as 5 feet (1.5 m), and focal lengths as great as 150 feet (45.7 m).

Most of the above machine tools are now in use at the instrument shop temporarily occupied in the Seward Building, between Colorado and Union Streets. At present, two draftsmen, one instrument-maker, three machinists, and two pattern-makers are at work there, under the direction of Professor Ritchey. No optical work can be done until the new shop is completed.

It is probable that offices for a staff of computers will ultimately be provided adjoining the instrument shop.

EXPERIMENTS WITH FUSED QUARTZ

As already stated, glass mirrors are subject to change of figure when exposed to the Sun's rays. At the independent suggestion of Dr. Billings and Dr. Elihu Thomson, experiments have been undertaken with the object of using fused quartz instead of glass for the mirrors, since its coefficient of expansion is only about one-tenth as great. The work has been done by Professor Ritchey and Mr. Wingren, with the aid of a grant given last spring for this purpose by the Carnegie Institution. The quartz is easily fused in an electric furnace, but the fused mass is filled with fine bubbles, which increase in number and size as the temperature of the furnace is increased. An attempt is being made to eliminate the bubbles, in order to secure fused quartz for prisms and lenses. For mirrors, as Professor Ritchey suggests, blocks like those already obtained will probably serve very well, if the bubbles at one surface can be gotten out by remelting with the flame of an electric arc.

STAFF

The staff of the Solar Observatory is at present constituted as follows:

George E. Hale, Director.

G. W. Ritchey, Astronomer, and Superintendent of Instrument Construction.

Ferdinand Ellerman, Assistant Astronomer.

Walter S. Adams, Assistant Astronomer.

There is a post-office on Mount Wilson, about a mile from the Observatory, but the delivery of mail is so infrequent and irregular, that I conduct my correspondence from the Observatory Office in Pasadena, where letters for me should be addressed. Letters and printed matter for Professor Ritchey should be sent to the same address, but printed matter intended for me should be addressed to Mount Wilson, Cal., as my scientific library is at the Observatory. Printed matter for the Solar Observatory, and both letters and printed matter for Mr. Ellerman and Mr. Adams, should be addressed to Mount Wilson.

Books and papers, especially on astrophysical subjects, will be gladly received for the library of the Solar Observatory. Sets of observatory publications, which are greatly needed, may be forwarded from abroad, free of expense, through the International Bureau of Exchanges of the Smithsonian Institution, which has offices in the principal cities of Europe. It is hoped that some return for such contributions may ultimately be made in the form of our own publications.

Mount Wilson, Cal.,
February 8, 1905.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 3

Reprinted from the *Astrophysical Journal*, Vol. XXIII, pp. 1–5, 1906

A PROGRAM OF SOLAR RESEARCH[1]

By GEORGE E. HALE

In an article on "Solar Research at the Yerkes Observatory"[2] I have given, in outline, a program of solar investigations prepared several years ago. Some of the investigations included in this program were carried out at the Yerkes Observatory, and others are still in progress there. As explained in another paper,[3] it was found that the solar spectrograph attached to the 40-inch telescope was of insufficient focal length for satisfactory photographic work on the spectra of sun-spots, and accordingly this work was postponed, and has recently been taken up at the Solar Observatory. For similar reasons it was found to be advantageous to delay other investigations until the completion of the Snow telescope. We are finally in a position, however, to attack the whole question seriously. I have therefore thought it might be of interest to publish the revised program of solar research which we are putting into operation on Mount Wilson.

In preparing this program, two principal purposes have been considered: (1) the study of the Sun as a typical star, with special reference to stellar evolution; (2) the study of the Sun as the central body of the solar system, with special reference to the relationship between solar and terrestrial phenomena.

The proposed investigations include:

I. DIRECT PHOTOGRAPHY

a) Daily photographs of the Sun on a scale of 6.7 inches (17 cm) to the diameter, for comparison with spectroheliograph plates.

b) Large-scale photographs of spots and other regions, for the study of details.

II. PHOTOGRAPHIC STUDIES OF THE SOLAR ATMOSPHERE WITH THE SPECTROHELIOGRAPH

a) Daily photographs of the Sun with the lines:

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[1] *Contributions from the Solar Observatory*, No. 3.

[2] *Astrophysical Journal*, **16**, 211, 1902.

[3] *Contributions from the Solar Observatory*, No. 5: "Photographic Observations of the Spectra of Sun-Spots."

(1) H_1, showing the calcium flocculi at low level.
(2) H_2, showing the calcium flocculi at higher level.
(3) H_2, showing the calcium flocculi at higher level and the prominences (composite photographs, with separate exposures for flocculi and prominences).
(4) $H\delta$, showing the hydrogen flocculi.
(5) Other dark lines, as may prove feasible, showing the flocculi of the corresponding elements.[1]

b) Measurement and discussion of the above photographs, involving:
(1) Determination of the area of the flocculi and their distribution in heliographic latitude and longitude. These results will give a measure of the relative activity of different elements in various regions of the solar surface; furnish the means of answering certain questions regarding the relationship of flocculi to spots, such as the time of first appearance, relative position on the disk, etc.; and serve for comparison with meteorological and magnetic records.
(2) Measurement of the heliocentric position of points in the flocculi that can be identified on several successive photographs, to determine the law of the solar rotation for the corresponding elements.
(3) Determination of the position, area, and brightness of eruptive phenomena, to find whether they are related to other phenomena of flocculi or spots, to possible changes in the absorption of the solar atmosphere, and to auroras and magnetic storms.
(4) Measurement of the area and brightness of the neutral or bright regions near sun-spots, on photographs of the hydrogen flocculi, for comparison with other phenomena, such as the velocity of ascending and descending currents of calcium vapor, the intensity of radiation (for given wave-lengths) of the spots and neighboring regions, etc.
(5) Study of the motion of the high-level calcium vapor, especially in flocculi overhanging sun-spots, to determine the direction and velocity of horizontal currents.
(6) Measurement of the position and area of prominences, and study of their relationship to solar and terrestrial phenomena.

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[1] λ 4045, showing the iron flocculi, is now used daily.

c) Special studies with spectroheliographs of suitable dispersion, involving the use of various dark lines (including enhanced lines) and of lines affected in spots; simultaneous photographs of eruptions on the disk in different lines; comparative studies of quiescent and eruptive prominences with the hydrogen and calcium lines, etc.

III. SPECTROSCOPIC INVESTIGATIONS

a) Daily photographs of the spectra of spots, region $H\alpha$ to $H\beta$, for the determination of intensities and the identification of lines that are widened or otherwise affected.[1]

b) Photographs of the H (or K) line, with high dispersion, on successive sections of the disk, to give the radial velocity of the calcium vapor in the flocculi, chromosphere, and prominences.

c) Measurements with the bolometer of the relative radiation, corresponding to various wave-lengths, of the sun-spots, faculae, and photosphere; and bolographs of spot spectra.

d) Spectrographic measurements of the solar rotation, to determine the law of rotation with the lines of various elements, and to detect possible changes in the rotation period. (See also II, *b*), 2.)

e) Miscellaneous investigations, as opportunity may offer, of the spectrum of the chromosphere; the pressure in the solar atmosphere, etc.

IV. STUDIES OF THE TOTAL SOLAR RADIATION

a) Frequent determinations of the total solar radiation, involving measures with the pyrheliometer at various altitudes of the Sun, and simultaneous bolographic records to give the absorption of the Earth's atmosphere.

b) Frequent determinations of the absorption of the solar atmosphere for light of various wave-lengths, to detect any possible changes in absorption that might account for observed changes in the total radiation.

c) Occasional supplementary observations on Mount San Antonio, (24½ miles = 39.4 km from Mount Wilson) at an altitude of 10,100 feet (3,050 m).

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[1] These photographs may also serve to record such exceptional phenomena as the remarkable disturbance of the reversing layer described in a previous paper (*Astrophysical Journal*, **16**, 220, 1902).

d) A comparative study of different types of pyrheliometers.

V. LABORATORY INVESTIGATIONS

a) A study of the lines affected in sun-spots under various conditions of temperature, pressure, etc.
b) Determinations of the pressure-shifts of certain solar lines.
c) Other similar investigations.

With a few exceptions, these investigations are now in progress at the Solar Observatory. Direct photographs of the Sun are taken daily, but large-scale photographs of details have not yet been started. The daily spectroheliograph routine includes H_1, H_2, $H\delta$, and λ 4045 (*Fe*) photographs of the disk, and H_2 (composite) photographs of the flocculi and prominences, all on a scale of 6.7 inches to the Sun's diameter. (See *Contribution* No. 7.) Special studies with the spectroheliograph are also in progress. An account of the work on spot spectra and on the motion of the calcium vapor may be found in *Contributions* Nos. 5 and 6. Special apparatus for the spectrographic study of the solar rotation has been nearly completed in our instrument shop. The study of the solar radiation has so far been confined to the investigations of the Smithsonian Expedition (June–November 1905), but arrangements have been made to continue this work next year. In the laboratory an investigation has been undertaken of the effect of a magnetic field on lines that are widened in sun-spots.

There are many solar investigations not included in this program which offer important returns to careful observers. In visual observations attention may well be directed to such matters as the brightness of the inner extremities of the penumbral filaments; the relative width of these filaments in large and small spots; the evidence for and against cyclonic motion in spots; the changes in the peculiar patterns frequently assumed by the photospheric granules; the character of the granulation in the faculæ, etc. Large-scale photographs, like those of M. Janssen, may also be used in the study of such questions, but the most minute phenomena can be observed only visually. The chromosphere and prominences offer an excellent field for the visual study of details, in addition to the statistical studies of the Italian spectroscopists and other observers, which should be continued and extended. At times of good definition, the spectrum of the chromosphere will richly repay observation with powerful instruments. The same may be said of spot spectra, where many observers can find profitable employment.

The above investigations are mentioned merely as examples of the innumerable opportunities open in solar research. As I hope to show at some future time, the amateur, even if his instrumental equipment be a very modest one, may do work of the highest value, if he will plan it intelligently. A careful consideration of the requirements of promising researches, and a willingness to co-operate with others, should enable any observer to contribute in an important way to the progress of solar physics.

Mount Wilson, California,
December 1905.

Contributions from the Solar Observatory of the Carnegie Institution of
Washington, No. 4
Reprinted from the *Astrophysical Journal*, Vol. XXIII, pp. 6–10, 1906

SOME TESTS OF THE SNOW TELESCOPE[1]

BY GEORGE E. HALE

In *Contributions from the Solar Observatory*, No. 2, I have given a brief description of the Snow telescope and the house in which it is mounted on Mount Wilson. At the time that paper was written the telescope was not yet in working order, and it remained to be determined whether it would prove capable of giving the results expected from it. I am glad to say that it has since been completed and successfully used in a variety of work. It is believed that an account of the experience so far gained with this telescope may be of service to others who may intend to use similar instruments.

The cœlostat and second mirror are shown in Plate VI, a view taken from within the sliding shelter which covers these parts of the instrument when not in use. The cœlostat mirror is 30 inches (76 cm) in diameter, and the second (plane) mirror, which sends the beam from the cœlostat to the concave mirror in the north end of the telescope house, has a diameter of 24 inches (61 cm). The second mirror can be moved along rails, so as to receive the reflected beam from objects at different declinations. The cœlostat and second mirror stand on a stone pier 29 feet (8.8 m) high at its south end and 25 feet (7.6 m) high at its north end. A house, of steel construction covered with canvas louvres, surrounds the pier and affords space in the extension toward the north for the concave mirrors and the spectroheliographs and spectroscopes. The concave mirror, shown in Plate VII, has an aperture of 24 inches and a focal length of 60 feet (18.3 m). A second concave mirror of the same aperture and of 143 feet (43.6 m) focal length is under construction in our optical shop, and will soon be mounted in the long extension of the house which lies beyond the canvas partition now temporarily in place near the 60-foot mirror.[2]

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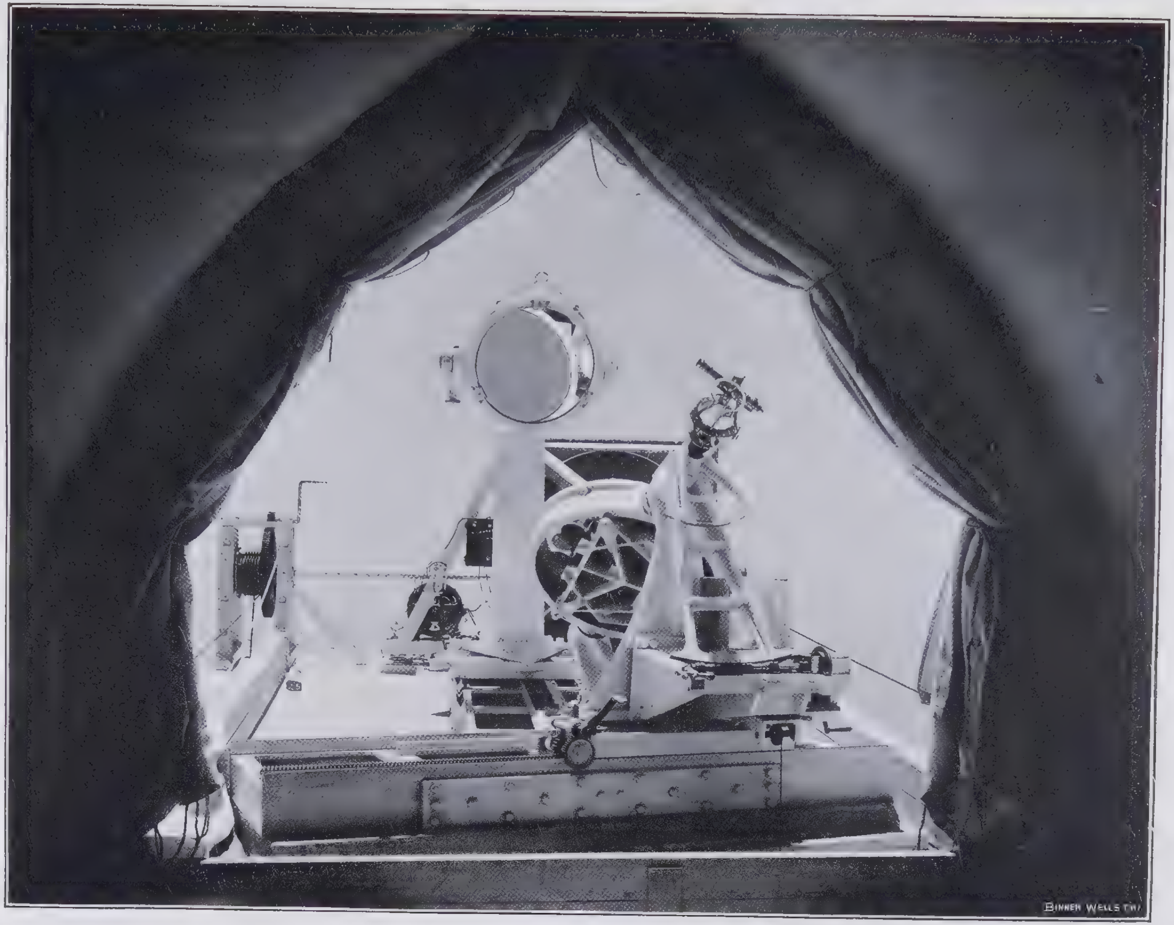
[1] *Contribution from the Solar Observatory*, No. 4.

[2] For a plan and elevation of the Snow telescope house, together with photographs showing its manner of construction, and a further account of the instrument, see *Contributions from the Solar Observatory*, No. 2, and the *Report of the Director of the Solar Observatory for the Year Ending September 30, 1905*.

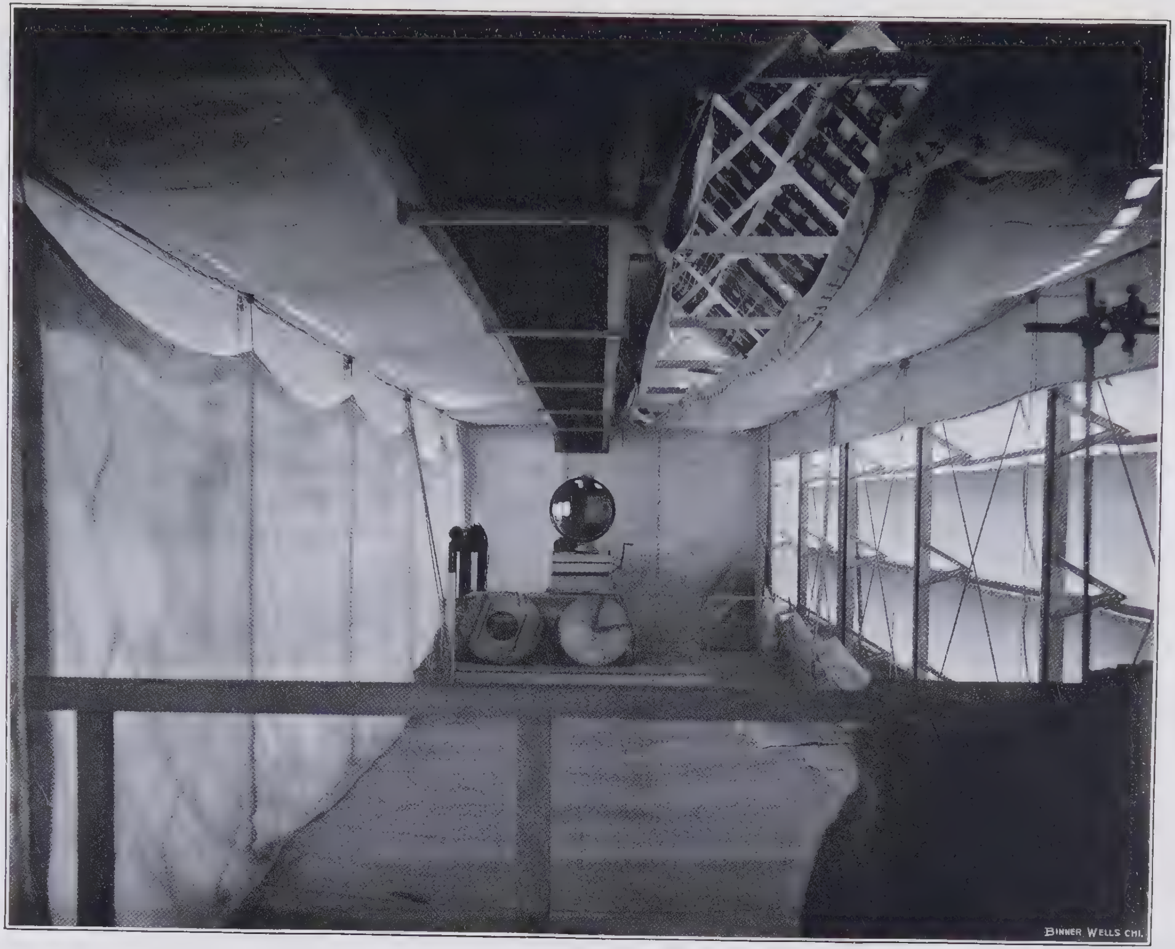
In the preliminary tests of the Snow telescope at the Yerkes Observatory, the results were rather disappointing, though good images were occasionally obtained. It was evident that difficulty might be expected from the distortion of the mirrors by the Sun's heat, and in the first experiments on Mount Wilson this expectation was realized. Soon after the exposure of the mirrors to the Sun it was seen that the focal length was increasing, and, as the focus changed, evidence of the astigmatism of the mirrors made itself apparent in the appearance of the image inside and outside the focal plane. Since the change of focus amounted in some cases to as much as 12 inches (30.4 cm), and since the astigmatism under such circumstances was very marked, it was feared that great difficulty would be experienced in the use of the telescope, particularly as the focus at opposite limbs of the Sun on one occasion differed by as much as 3 inches (7.6 cm). The changes of focal length at different times did not seem to be the same, even for equal altitudes of the Sun. This was soon traced to the change in the amount of heat absorbed by the mirror as the silver film deteriorated in use. Another variable, as subsequent experiments proved, was introduced by the strength of the wind and the temperature of the air blown across the mirror surface. On a day with a cool breeze the focus changed less than on a day with no wind. Naturally enough, the height of the Sun above the horizon proved to be a very important factor, so that the focus changed much more rapidly near noon than early in the morning.

From the outset, the advantages of observing the Sun during the early morning hours had been apparent. In view of the difficulties that were being experienced, this point was again carefully investigated, and it was soon found that with the Snow telescope the finest definition is to be expected about one hour after sunrise. At this time the mountain is but little heated, and the atmospheric absorption reduces the intensity of the solar radiation to such a degree that the mirrors change their figure slowly. If the mirrors are shielded from sunlight between exposures of photographs, and if the exposure time is made as short as possible, excellent results can be obtained



Coelostat and Second Mirror of Snow Telescope

PLATE VII



Concave Mirror of Snow Telescope

during a period of about an hour in the early morning, and usually during a similar period not long before sunset.

It must be understood that the precautions mentioned are necessary only when it is desired to secure the finest possible definition of the solar image. When such precautions are used, the average photographs taken during the summer in the early morning with the Snow telescope and temporary spectroheliograph are but little inferior to the best photographs, secured on only a few days in the year, with the 40-inch Yerkes telescope and the Rumford spectroheliograph. The best photographs taken on Mount Wilson are distinctly superior to the best ever secured by Mr. Ellerman and myself with the 40-inch telescope. Unless these points were made clear, it might be supposed that no work could be done with the Snow telescope except under the conditions stated. As a matter of fact, however, very fair photographs can be obtained with the spectroheliograph at almost any time during a cool day, and in the early morning and late afternoon hours of a hot day without wind. It is only necessary to arrange the daily program of observations so that the spectroheliograph, which requires the finest definition, is used during the period when the seeing is best. Photographic work on the spectra of sun-spots follows, and after this is completed the conditions are entirely satisfactory for various other observations, such as bolographic work on the absorption of the solar atmosphere, etc.

The photographs reproduced in Plate VIII will give an idea of the results obtained with the Snow telescope. The spectroheliograph employed was put together for temporary use pending the completion of the permanent instrument. The only prisms available were some that had proved unsuitable (because of poor definition) for the Bruce spectrograph, and the slits were taken from old instruments. The optical train was mounted on a wooden platform, with cast-iron Λ-rails running on four steel balls resting on cast-iron V-rails attached to a wooden base. A small electric motor, belted to a pulley on the end of a long screw, provided the motive power. The screw was mounted on the wooden base, and passed through a nut attached to the platform. The numerous photographs obtained with this simple and inexpensive apparatus have served for a comparative study of the faculæ and the H_1 flocculi.

The ventilated house provided for the Snow telescope has proved so satisfactory that it has not seemed necessary to make further experiments on the use of Langley's method of stirring the air along the path of the beam. It is usually found best to lower the inner canvas wall on the side of the house away from the Sun, leaving the canvas wall on the opposite side of the house in place, so that the heated air under the louvres may pass upward and out through the ventilated roof, instead of entering the house and disturbing the beam (see Plate VII).

While fans have not been employed for stirring the air, they have nevertheless been used to advantage in blowing the mirrors, for the purpose of preventing a rapid change of figure. In the first experiments, a fan 4 feet in diameter, driven by an electric motor, was mounted at the south end of the cœlostat pier. Air from this fan was led to the cœlostat mirror and the second mirror through large canvas tubes. In these experiments the concave mirror did not receive a blast of air, as it was thought the effect could be detected sufficiently well if only the first and second mirrors were cooled in this way. As it was found that the focus could be varied through a considerable range by blowing the first two mirrors, arrangements have been made to cool all the mirrors in the same way. The small electric fans to be used for this purpose will be operated while the adjustments of the spectroheliograph are being made, and also between exposures, when the mirrors are also shielded from the Sun by an adjustable canvas screen.

Excellent definition is obtained at night with the Snow telescope, except when the mirrors have been exposed to the Sun for some hours during the afternoon. On such occasions the rapid change of figure during the early evening results in irregular distortions, as indicated by the multiple images sometimes observed. Without such previous exposure to the Sun, the images of the stars and of the Moon leave nothing to be desired. Nevertheless there is a considerable change of focal length during the night, but this would be inappreciable during short exposures, and during long exposures on stellar spectra it is only necessary to correct the focus by changing the position of the concave mirror from time to time.

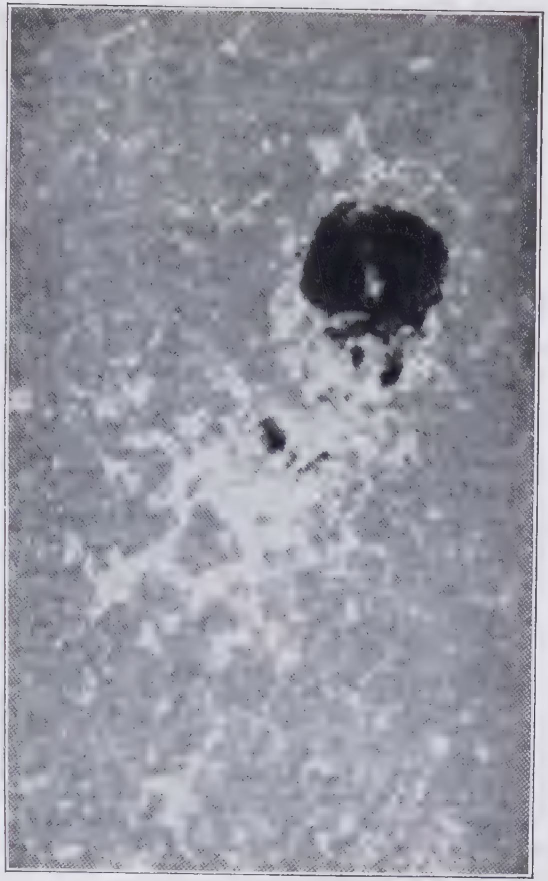


FIG. 1

July 17, 1905, 7^h 56^m. Low-Level Calcium Flocculi
Slit Set on H_1 (λ3966). Sun's Diameter =0.28 meter

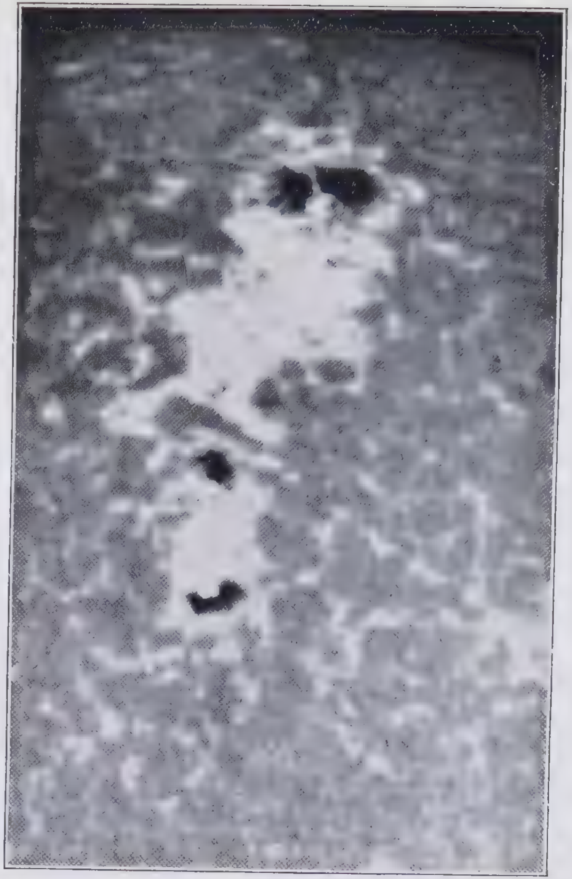


FIG. 2

July 20, 1905, 5^h 18^m. High-Level Calcium Flocculi
Slit set on H_2. Sun's Diameter=0.28 meter

It is to be hoped and expected that materials more suitable than glass can be obtained for the mirrors of telescopes which are to be used for solar work. Some preliminary tests of small mirrors of "Invar" (nickel-steel of the lowest coefficient of expansion), made by Hilger, indicate that this material can hardly be used, since it is too soft, in Professor Ritchey's opinion, to permit a large optical surface, even if once produced, to be kept well polished and free from scratches. It is probable that speculum metal could be used with a fair degree of success, since such a good conductor of heat would presumably act very differently from a poor conductor like glass. I am informed by Mr. Brashear that when speculum metal grating-plates are being figured, tests can be made very much sooner after polishing than is possible in the case of glass. This indicates that the figure is changed less by the heat produced by friction. Our attempts to produce disks of fused quartz have not yet been successful enough to demonstrate that mirrors can be made of this material.

From a mechanical standpoint the Snow telescope has proved to be completely successful. From an optical standpoint it has shown itself capable of giving results with the spectroheliograph superior to those obtained in our work with the 40-inch refractor. In view of the advantages it offers for many classes of astrophysical research, this telescope may now be considered to have passed the experimental stage, though the possibility of providing better material for the mirrors indicates that its optical performance will probably be considerably improved in the future.[1]

MOUNT WILSON, CALIFORNIA,
November 1905.

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[1] For an account of recent work with the Snow telescope, see *Contributions*, Nos. 5, 6 and 7

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 5
Reprinted from the *Astrophysical Journal*, Vol. XXIII, pp. 11–44, 1906

PHOTOGRAPHIC OBSERVATIONS OF THE SPECTRA OF SUN-SPOTS[1]

BY GEORGE E. HALE AND WALTER S. ADAMS

INTRODUCTION

In the *Astrophysical Journal*, **16,** 217, 1902, an account is given of experiments in photographing the spectra of sun-spots made at the Yerkes Observatory in 1902. The spectrograph employed in this work was provided with collimator and camera of 3¼ inches (8.3 cm) aperture and 42½ inches (108 cm) focal length, and a plane grating having 20,000 lines to the inch (7,874 to the centimeter), used in the second spectrum. With the same spectrograph the more conspicuous of the widened lines had been photographed at the Kenwood Observatory some years previously, but the 2-inch (5 cm) solar image given by the 12-inch (30 cm) Kenwood refractor was found to be too small for satisfactory work. At the Yerkes Observatory the spectrograph was attached to the 40-inch (102 cm) telescope, and the 7-inch (18 cm) solar image proved to be large enough for all but the smallest spots. Many widened lines were photographically recorded, and the spot "bands" were partially resolved into lines, some of which were measured on the plates. The linear dispersion of the spectrograph, however, was quite insufficient to permit more than a small part of its resolving power to be realized photographically. For this reason the continuation of the work was deferred until a suitable spectrograph could be obtained. Since this instrument was to have a focal length of 18 feet (5.5 m), it could not be attached to the 40-inch telescope. For this reason it was decided to carry on the work with a long-focus horizontal telescope, then in process of construction in the instrument shop of the Yerkes Observatory.

INSTRUMENTS EMPLOYED

The experiments were resumed last August on Mount Wilson, with the aid of the Snow telescope, which gives a solar image 6.7 inches (17 cm) in diameter when the concave mirror of 24 inches

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[1] *Contributions from the Solar Observatory*, No. 5.

(61 cm) aperture and 60 feet (18.3 m) focal length is employed. In some of the experiments the image was enlarged to a scale of 16 inches (41 cm) to the Sun's diameter, by means of a Brashear concave amplifying lens; but while good results were obtained in this way, it was thought best to use the 6.7-inch image until the completion of the 24-inch mirror of 143 feet (45.7 m) focal length, which will give a 16-inch solar image without amplification.

The 6-inch (15 cm) objective of 18 feet (5.5 m) focal length for the Littrow (auto-collimating) spectrograph was under construction by the Zeiss Co., and no large grating was available. We were fortunate, however, in having the use of a 4-inch (10 cm) visual objective of 18 feet focal length, and a 4-inch grating, having 14,438 lines to the inch (5,672 to the cm), both belonging to the Yerkes Observatory. The slit of the Littrow spectrograph is mounted immediately below the photographic plate, to which the spectrum is returned by tilting the grating back through a very small angle. Light from the slit reflected toward the plate by the 4-inch objective is eliminated by pasting small pieces of paper to the inner surface of the lens. The plate-holder can be moved vertically by means of a rack and pinion, thus permitting several spectra to be photographed side by side on a single plate $3\frac{1}{4}\times 10$ inches (8.3×25.4 cm). As the distance from the center of the slit to the center of the spectrum is only $5\frac{3}{4}$ inches (14.6 cm), the astigmatism, which is at right angles to the direction of dispersion, is too small to be noticeable. The definition of the spectrograph is excellent visually, but in view of the comparatively long exposures required in the third-order spectrum, the present work has been done in the second order, where the linear dispersion is insufficient to secure complete photographic resolution. For this reason we hope to obtain better results when a larger objective and grating have been provided for the spectrograph.

At this point a few words may be said regarding the relative advantages of the visual and photographic methods of observing spot spectra. The visual method permits the finest details of the spectra to be seen, and thus renders possible the separation of close lines and the observation of such narrow reversals as Mitchell has recently recorded. Advantage can be taken of the moments of best definition, and none of the various phases of rapidly changing eruptive phenomena need be lost, as they may be in photographic work where exposures of several minutes are required. For these reasons visual observations cannot be wholly supplanted by photography, in spite of the numerous advantages of the latter. These include:

1. The possibility of recording, during brief periods of fine definition, the entire spectrum of several spots, leaving the work of measurement and identification of the lines to be done at leisure.

2. The high degree of precision attainable in measurements of the photographs, insuring correct identification of lines and the detection of small displacements caused by motion or pressure.

3. The ease of acquainting other observers, through the publication of photographs, with the exact nature of the results obtained, thus reducing the danger of such misunderstandings as are common in connection with visual work.

The plates used in our work are the Cramer Instantaneous Isochromatic, which have a maximum of sensitiveness at about λ 5600. With suitable exposure-time these plates cover the region from near the D lines into the blue-green. It would, of course, be possible to go farther to the red by extending the time of exposure sufficiently, but the curve of sensitiveness in this region is so steep that only a very small extent of spectrum would be properly exposed at any one time; and so it has seemed preferable to wait until specially sensitized plates become available for this work. The region which we include in our present discussion extends accordingly from λ 5000 to about λ 5850.

Table I gives in detail Mr. Adams' estimates of intensity and identifications with Rowland's solar lines for the widened lines upon ten of the plates, L 17 . . . . L 43. The individual determinations of intensity are given in order to show about what degree of accordance is to be expected among separate observations. As stated above, we have adopted Fowler's plan of estimating the spot lines in terms of Rowland's intensities, beginning with 0000, which represents a line at the limit of visibility, and going upward through 000, 00, 0, 1, etc. Intermediate intensities are denoted by a dash between the preceding and the following value: thus, 1–2 denotes a line whose intensity is midway between 1 and 2 of Rowland's scale. In practice this system has proved very convenient. The spectrum of the spot has on either side the spectrum of the disk for comparison purposes, the intensities of the two having been made as nearly as possible the same through suitable exposure time. Accordingly, in examining the plates under a low-power microscope, the observer has in the same field of view with the spot spectrum a large number of lines of the comparison spectrum showing a wide range in intensity. The estimation of the intensities of the spot lines in terms of these then becomes very simple.

The first three columns of the table give Rowland's wave-lengths for the lines, the elements to which they are due, and their intensities in the Sun. The fourth column gives their intensities in the spots and is made up of the means of the succeeding columns. It is placed next to the column of Solar Intensities for convenience in comparison. The abbreviation "n. c." for "no change" denotes that the line is not affected.

The linear scale of the plates is very closely 1.5 tenth-meters to the millimeter.

The list below does not include lines for which the mean of the determinations does not show a change of intensity amounting to one-half of a division on Rowland's scale. It also omits a considerable number of "band-lines" in the region λ 5300 to λ 5600, which we are at present engaged in identifying, and shall publish later. The "band-lines" in the region λ 5000–λ 5200 are discussed elsewhere in this paper.

Visual determinations of the widened lines in this region of the spectrum have been published by many observers. The latest of these is that of W. M. Mitchell,[1] and a comparison of the results obtained by the two methods is of considerable interest. It should, however, be remembered that the list of lines given here is based upon but ten plates, and that these include only three separate spots, while Mitchell's results are derived from a much greater number. Excluding the "band-lines" in the region λ 5030–λ 5215, Mitchell's list gives a total of 352 lines between λ 5000 and λ 5850 which are affected. The table above gives a total of 345. Of these, 267 are common to both lists; 85 are given by Mitchell which do not occur in our list; and 78 are given above and are not found in Mitchell's table. The

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[1] *Astrophysical Journal*, **22**, 4, 1905.

TABLE I

LINES AFFECTED ON THE PHOTOGRAPHS

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5009.83	*Ti, Co*	00	1–2				1–2	1–2						
5013.48	*Cr, Ti*	2	2–3				2–3	2–3						
5016.34	*Ti*	2	3				3	3						
5017.76	*Ni*	3	3				n. c.	n. c.						Winged
5020.21	*Ti*	2	3				3	3						
5021.78	*Fe*	0	1				1–2	0–1						Hazy
5022.11	*Cr*	000	0				0–1	0						
5023.05	*Ti*	2	2–3				2	3						
5025.03	*Ti*	3	4				4	4						
5025.75	*Ti*	1	2				2	1–2						
5027.30	*Fe*	3	4				4	4						Rowland's intensity poor
5027.94	*Fe*	1	0				0	0		0–1				
5029.66	. . .	0000	00–0					0		00				
5036.64	*Ti*	2	3				3	3		3				
5038.58	*Ti*	2	3–4				3–4	3–4		3				
5039.43 }	*Fe*	3	} 4				4	4		4				Winged
.54 }	*Ni*	00												
5040.14	*Ti*	3	4				3–4	4		4				
5040.79	*Ti*	00	1				0–1	1		1				
5043.76	*Ti*	00	0–1				n. c.	0–1		1				
5045.58	*Ti*	00	0–1				0–1	0		1				
5048.61	*Fe*	3	2–3				2	2		n. c.				
5052.08	*Cr*	0	0–1				0–1	0–1		0–1				
5053.06	*Ti*	0	1				1	0–1		1				
5058.67	*Fe*	00	0					0		0				
5060.26	*Fe*	3	3–4		n. c.	4	n. c.	4		4	n. c.			
5062.28	*Ti*	0	1		0–1	1	0–1	1		1	0–1			

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5064.84	*Ti*	3	4		3–4	3–4	4	4		4	4			
5066.08	*Cr*	000	1–2		1	1–2	1	2		2	2			Blend
.17	*Ti*	000												
5066.91	...	00	0		0	0	0–1	0		0				
5068.48	*Cr, Ti*	0000	0				00–0	0		0				
5071.67	*Ti*	0	1		1	1	1	1		1–2	1			
5073.11	*Cr*	1	1–2		n. c.	1–2	1–2	2		2	n. c.			
5073.92	...	000	0				0	0		00–0				
5080.71	*Ni*	4	3–4		3–4	n. c.	3	3		n. c.	3			Hazy
5082.53	*Ni*	2	1		1	1	1	0		1	0–1			
5083.88	...	000	00			0	00	00		00				
5085.34	*Ti*	0000	00				00	00						
5086.95	...	000	0		0–1	0	0–1	0		00				
5087.24	*Ti*	0	2		1–2	2	2	2		1–2	2			
5092.28	...	0000	0				0	0						Probable blend
.48	...	00												
5094.20	...	000 N	0			00–0		0						
5110.57	*Fe*	5	5–6		n. c.	6	5–6	6		6	n. c.			Hazy
5113.30	*Cr*	00	0		n. c.	0	0	0		0–1	0			
5113.62	*Ti*	0	1		1	1	1	1		1–2	1			
5115.96	*Fe*	0	00–0			00	00	0		00				
5120.59	*Ti*	0	0–1		0–1	1	1	1		n. c.	n. c.			
5120.80	...	000	00–0			0	00–0			00				
5121.73	*Ni*	0	1–2		1–2	1	1	1		1–2	2			Thinned on violet edge
.82	*Fe*	2												
5122.97	*Co*	000	0–1		0	0–1	0	1		0–1				
5123.64	*Cr*	000	00		n. c.	00	00	00		00–0	00–0			
5127.86	...	00	0		n. c.	0	0	0		1	0			
5129.80	*Fe*	1	00		00	000	00	00		0	000			

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5131.64	*Fe*	2	1–2		n. c.	1	1	n. c.		n. c.	1			
5132.84	. . .	00	000		n. c.	n. c.	000	0000		0000	000			
5136.27	*Fe*	00	1		1	1	1	1		0–1	0		0–1	
5137.25	*Ni*	3	3–4		4	3–4	4	n. c.		n. c.	4		n. c.	
5139.43	*Fe*	4	9		10	8	10	8		10	9		10	Winged
.64	*Fe*	4												
5141.92	*Fe*	3	3–4		4	4	n. c.	n. c.		n. c.	n. c.		4	Hazy to violet
5144.85	*Cr, C*	00	1				1	1					0–1	Hazy
5147.65	*Ti*	0	2		1–2	1–2	1–2	2		2	2		2	
5148.41	*Fe*	3	3–4		n. c.	3–4	n. c.	3–4		n. c.	4		4	
5152.09	*Fe*	3	4		4	4	4	4		n. c.	4		4	Fringe on violet edge
5152.36	*Ti*	0	1		0–1	1	1	1		1–2	1		1	
5156.82	*C, —*	00	1				0–1	1						
5159.23	*Fe*	2	1		1	1	1–2	1–2		1–2	1		1–2	
5164.72	*Fe ?*	1	0–1		0	0–1	0–1	0–1		n. c.	0		0	Bright space at 5163.7
5166.45	*Cr, Fe*	3	3–4		3–4	3–4	3–4	4		4	4		n. c.	
5169.07	*Fe*	3	5		5	5	5	5		6	5		6	Weak on red edge
.22	*Fe*	4												
5176.95	*V*	000	0		0	0	0	0–1		0	00–0		0	
5177.41	*Fe*	0	1–2		1–2	1–2	1	1		1–2	1		1–2	Hazy
.58	*Co*	00												
5187.62	. . .	000	0		0	0	0	00–0		00	0		0	
5188.08	*Fe*	1	0–1		n. c.	0–1	0–1	0–1		n. c.	0–1		0–1	
5188.86	*Ti*	2	6		6	6	6	6		6	n. c.		6	Hazy toward violet
89.02	*Ca*	3												
5191.63	*Fe*	4	5	5–6	5	5	5	5		5	5		n. c.	Hazy
5192.16	*Cr*	00	0		0	0	00	0		0–1			0	
5195.11	*Fe*	4	5	5	5	5	5	5		n. c.	5		n. c.	Winged
5196.23	*Fe*	1	2	2	2	2	n. c.	n. c.		2	2		2	Fringe on violet edge

TABLE I—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5196.61	*Cr*	0	1		1	1	0–1	0–1		1–2			2	Widening due to *Mn* component probably
.74	*Mn*	00												
5197.33	*Ni, Mn*	00	0–1					0–1					0–1	
5197.74	. . .	2	0–1			0	0	0–1		1			1	
5198.89	*Fe*	3	4	5	4–5	4	4	4		4	4		4–5	
5200.36	*Cr*	00	00–0	0	n. c.	n. c.	n. c.	0		00–0	00–0		00–0	
5201.26	*Ti*	000	0	0	0	0–1	0	0		0	0		0	
5204.68	*Cr*	3	10	10	10	9	10			10	10		10	Fringe on violet edge
.77	*Fe*	5												
5206.22	*Cr-Ti*	5	6	7	7	6	5–6			6	6		6	
5208.60	*Cr*	5	6	5	7	6	6			6	5		6	
5210.56	*Ti*	3	5	4	5	5	5			5	5		5	Hazy
5212.86	. . .	000 Nd?	0							0			0	
5214.29	*Cr*	00	0		0–1	0	0			0			0	
5214.78	. . .	00	0		0–1	0	0			0			0	
5218.08	*Fe*	0	0–1	1	0–1	0	n. c.			n. c.	0–1		1	
5221.93	*Cr*	0	1	1	0–1	0–1	1			0–1	1		1	
5222.56	*Cr*	00	00–0	00	0	00–0	00–0			00–0	n. c.		00–0	
5222.85	*Ti, Cr*	00	0	00	0–1	0	0			0	0		0	
5223.79	. . .	000	0	0	0	0	00			0	0		0	
5224.24	*Cr*	000 N	00–0							00–0			00–0	
5224.47	*Ti*	0	1	1	1	1	1			1	1		1	
5225.10	*Cr*	0	1–2	1	2	1–2	1			2			1–2	
.20	*Cr, Ti, Fe*	00												
5225.70	*Fe*	2	3	3	3	3	2–3			3–4	4		3	
5227.04	*Fe-Cr*	3	4	4	4	4	4			4	3		3–4	
5230.38	*Co, Cr*	00	1	1	1	1	0–1			1	1		0–1	
5233.12	*Fe*	7	8	8	8	8	7–8			n. c.	8		8	Winged
5234.02	. . .	0000	00		00	00				00			0	

TABLE I—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5234·38	. . .	000	00		00	000				00			00	
5234·79	. . .	2	1	1	n. c.	1	0–1			1	1		1	
5235·35	*Co*	000	00–0	0	00	00	00			00	00		0	
5237·49	*Cr ?*	1	0–1	0–1	0–1	0–1	0–1			0–1	0		n. c.	
5238·74	*Ti*	000 N	1	0–1	1–2	1	1			1–2	1		1–2	
5239·14	*Cr*	00	0	0	0	0	0			0–1	0		0–1	
5241.04	. . .	000	00	00–0	00	00–0	00–0			00	00		n. c.	
5243·53	*Cr*	00	0	0	0	0	0			0			0	
5246.73	. . .	0000	00–0	0	0	00	00			00–0			00–0	
5247·23	*Fe*	2	1–2	1–2	1–2	n. c.	1–2			n. c.	2		2	
5247·74	*Cr*	2	2–3	2–3	2–3	n. c.	2–3			3	2–3		3	
5249·28	*Fe*	00	0	n. c.	0	0	0			0	0		0	
5250·38	*Fe*	2	3	3	3	2–3	2–3			3	3		3	
5251.67	. . .	. . .	00–0	00	0	00	00–0			00			0	Rowland gives no line here
5252.15	*Fe*	0	2	2	2	1–2	2			2	2		3	
.28	*Ti*	000												
5253·20	. . .	00	0	0	0	00–0	00			0–1	0		0	
5255·12	*Fe*	3	4	4	5	4	4			4–5	4		4	
5255·49	*Mn*	0	0–1	0–1	0–1	n. c.	0–1			n. c.	0–1		0–1	
5255·91	. . .	000	1	1	1–2	1	1–2			0–1	1		1	
·97	*Ti*	0000												
5260.14	. . .	000	0	0	0	0–1	00–0			00				
5260.56	*Ca*	0	1	1	1	1	1			1–2	1		1–2	
5264·33	*Cr*	4	9	8	9	8	9			10	9		9	
·42	*Ca*	3												
5264·98	. . .	0	00	00–0	n. c.	00–0	000			00	00		00	
5266·14	*Ti*	0	0–1	n. c.	1	0–1	0–1			0–1	n. c.		0–1	
5269·72	*Fe*	8 d?	9	10	8	9	10			10	8		9	Winged
5275·15	. . .	0	00	n. c.	00	00	000			00	00		n. c.	

TABLE I—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5275.34	*Cr*	00	2–3	2	2–3	2–3	2			2	2–3		2–3	
.45	...	1												
5275.93	*Cr*	1	2	1–2	2	2	2			2	1–2		2–3	Hazy
5280.54	*Fe*	1	1–2	1–2	1–2	1–2	n. c.			1–2	n. c.		1–2	
5282.58	*Ti*	00	1	0–1	1	1	1			1	1		1	
5284.60	*Fe, Ti*	00	0		0	0	0			00–0			00–0	
5284.79	...	00	00–0		00					00–0			0	
5285.82	...	000	00		0	00–0	00			00			00	
5287.35	*Cr*	000	0	0	0–1	0–1	0			0				
5289.45	...	000	00–0	00	0	0	00			00–0				
5290.98	...	000	00			0	00			00				
5295.96	Awv ?	00	1	0–1		1–2	1			1	1		0–1	
5296.87	*Cr*	3	4	4		4–5	4–5			4	3–4		4	
5297.41	*Cr, Ti*	000	00–0	00		0	00			00–0	00		0	
5298.46	*Cr*	4	6	5–6		6	6			6	5		6	Hazy
5300.15	...	00	0–1	0		1	0–1			0	0		1	
5300.93	*Cr*	2	3	3		3	3			3	3		3	
5301.22	*Co*	00	00–0	n. c.		0	0			n. c.	00–0		0	
5302.48	*Fe*	5	5–6	6		6	6			n. c.	6		n. c.	
5304.36	*Cr*	0	1	1		1	0–1			0–1			1	
5307.54	*Fe*	3	4	3–4		4	4			4	3–4		4	
5313.03	*Cr*	0	0–1	1		0–1	n. c.			n. c.	0–1		0–1	
5324.37	*Fe*	7	7	n. c.		n. c.	8			n. c.	n. c.		n. c.	Winged
5329.33	*Cr*	3	4	3–4		4	3–4		4	3–4	4		4	
5329.98	*Cr*	0	0–1	n. c.		n. c.	0–1		0–1	n. c.	0–1		0–1	
5331.64	*Co*	00d	0	0–1		0	00–0		0	0	0	0	1	
5335.05	*Co*	1	0	0		0–1	0		0	0	00	0–1	0	
5337.91	...	0	00						000	00		00		
5338.52	...	00 N	0–1	0		0–1	1		0	0		0	0–1	

TABLE I—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5341.21	*Fe*	7	10	10		10	10		10	10		10	10	Weak on red edge
.34	*Mn*	1												
5343.15	...	0000	00	00		00				00		000		
5344.94	*Cr*	00	00–0	0		00–0			0	0		n. c.		
5345.99	*Cr*	5	7	6		7			6	7	7		7	Winged
5348.51	*Cr*	4	6	6		7			6	6	6	6	6	Winged
5349.65	*Ca*	4	4–5	n. c.		5			n. c.	n. c.	5	5	n. c.	
5351.26	*Ti*	00	1	1		0–1			0	1	1	1	1	
5356.27	...	000	00	00–0		00			00	00–0		000–00	00	
5366.83	...	000	0	0		0			00–0	0	0	0–1	1	
5369.78	*Co-Ti*	1	2	2–3		2–3	2		2	1–2	2	2	3	
5371.66	*Cr?*	4	10	10		10	n. c.		10	10	10	10	10	Winged
.73	*Fe*	3												
5373.90	*Fe, Cr*	2	2–3	n. c.		2–3	n. c.		2–3	2–3	2–3	n. c.	2–3	
5384.83	...	000	00–0	00		00	00–0			00		00–0	00–0	
5387.16	*Fe, Cr*	0	1	0–1		1	1		1	0–1	1	1	1	
5387.77	*Cr*	00	1	0–1		1	1		0–1	0	0	1–2	1	
5389.37	...	000	0–1	0		0	0–1		0	0	0	1	1–2	
5390.05	...	00	0	0		0	0		n. c.	0	0	1	0–1	
5393.38	*Fe*	5	5–6	n. c.		5–6	6		n. c.	6	6	n. c.	n. c.	
5394.84	*Mn*	1	4	3		4	4		4	4	3	4	4	Diffuse
.91	*Mn*	1												
5396.78	*Ni*	000 N	1	1		1	0		0	1	0–1	1–2	1–2	
5397.34	*Fe*	7 d?	9	8		9	8		8	10	8	10	9	Winged
5399.68	*Mn*	1 Nd?	1–2	2		1–2	1–2		1–2	1–2	2	1–2	1–2	Hazy
5401.47	...	0	1	0–1		0–1	1		1	1	1	1	1	
5404.36	*Fe*	5	5–6	n. c.		n. c.	6		6	n. c.	6	n. c.	6	
5405.55	...	1	1–2	2		1–2	1–2		n. c.	1–2		1–2	n. c.	
5405.99	*Fe*	6	8	8		8	8		7	8	7	8	8	Winged

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5407.59	*Mn*	0	2–3	2		2–3	2–3		2	2–3	2	2–3	2–3	Diffuse
.69	*Mn*	0												
5409.02	. . .	000	0	0			0		00	00	00–0	1	1	
5410.00	*Cr*	4	6	5		6	6		n. c.	6	5–6	7	7	Fringe on violet edge due to *Ti* line
5413.00	*Mn*	00	00–0	0		n. c.	n. c.		00–0	00–0	0	0	00–0	
5413.89	*Mn*	00 N	0	0		00–0	00–0		n. c.	0	0	0–1	0	
5419.42	A ?	0000	00	000		00–0	00–0					0	00	
5420.51	*Mn*	0 N	3	2–3		2	3		3	3	2–3	3	3	Rowland's intensities poor
.61	*Mn*	0 N												
5425.46	. . .	1	0–1	0–1		0–1	n. c.		0–1	0	0–1	n. c.	n. c.	
5426.47	. . .	00	2	2		2	2–3		1–2	1–2	2	2	2	
5429.35	. . .	00	00–0	0		n. c.	00–0		00–0	0	00–0	0	00–0	
5429.91	*Fe*	6	8	7		8	7		8	8	7–8	8	n. c.	Hazy
5432.75	*Mn*	1	3	2–3		2–3	3		2–3	2–3	3	3	3	
5436.80	. . .	1	2	2		2	1–2		1–2	2	1–2	2	2	
5438.51	. . .	000	0	00–0		00	0		0	0	0	0–1	00–0	
5440.86	. . .	000	00–0	00		00	00–0			00		0	00–0	
5442.63	*Fe*	00	0	0		0	0		0	n. c.	0	1	0	
5447.13	*Mn*	6	8	8		8	8		8	7	8	8	n. c.	Winged
5448.58	*Fe*	00	00–0	0		0	00		00–0	00–0		00–0	n. c.	
5453.86	. . .	000	00–0	00		00	00–0		0	0	00	0–1	0	
5457.64	*Mn*	000	0	0		0	00–0		0	00–0	0	0	00	Hazy
.70	*Mn*	000												
5460.72	. . .	00	2–3	2		2–3	2–3		2	2	2	3	3	
5461.76	. . .	0	1	1		1–2	1		1	0–1	0–1	1	0–1	
5464.18	*Cr*	000	00	00		0	00		00	00	00	00	00–0	
5465.94	. . .	. . .	0									0	00–0	Rowland gives no line here
5470.80	*Mn*	0	2–3	2		2	2–3	2–3	3	3	2	3	3	Hazy
.88	*Mn*	0												

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5471.41	*Ti*	000	1–2	1		1–2	1–2	1–2	1–2	1–2	1	1–2	1–2	
5473.37	. . .	00	00–0	00–0		0	00–0	0	n. c.	0	0	00–1	n. c.	
5474.44	*Ti?*	00	0	0		0	0	0	0	0	0	1	0–1	
5474.96	. . .	0000 N	00–0					0			00–0	00–0	00–0	
5477.90	*Ti*	00	1–2	1		1–2	1–2	1–2	1	1	1	2	1–2	
5482.08	. . .	00	1–2	1		1–2	1–2	1–2	1	1	1	2	1	
5482.47	. . .	000 N	00–0									00	0	
5483.57	*Co*	1 d?	1–2	1–2		1–2	1–2	1–2	1–2	1–2		1–2	n. c.	
5484.85	. . .	000	00–0	00		00	00–0	0		00–0	0	0	00–0	
5485.76	. . .	000	0									00–0	0	
5488.37	. . .	00 Nd?	1	0–1		1	0–1	1	1	1	1	1	1	
5490.37	*Ti*	0	3	3		2	3	3	3	3	3	3	3	
5490.90 }	. . .	0	} 1–2	1		1–2	1–2	1–2	0–1	1	1	1–2	2	Widening due to red component mainly
91.04 }	. . .	000												
5493.71	*Fe*	1	1–2	n. c.		1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2	
5494.68	*Fe*	0	0–1	n. c.			0–1	0–1	0–1	1	1	0–1	0–1	
5495.10	*Ni*	00	0	0			00–0	00–0	0	00–0	0	0	0	
5495.66	. . .	. . .	00–0					0	00			00–0	00	Rowland gives no line here
5496.12	. . .	0000	00									00	00	
5497.74	*Fe*	5	6	6		n. c.	n. c.	n. c.	7	8	6	n. c.	7	
5504.12	*Ti*	0	1	1		1	1	1	1	1	1–2	1	1	
5506.10	*Mn*	1	2	1–2		1–2	1–2	2	2	2	2	1–2	2	
5507.00	*Fe*	5	7	6		6	6	7	7	7	6–7	7	7	Winged
5512.01	. . .	00	0	0		0	0	0	0	00–0	0	1	0	
5512.74	*Ti*	2	3	3		3	3	3	3	3	3	3	3	
5514.56	*Ti*	2	3	2–3		3	2–3	3	3	3	2–3	3	3	
5514.75	*Ti*	2	2–3	2–3		3	2–3	2–3	2–3	2–3	2–3	3–4	2–3	
5516.95 }	*Mn*	0	} 2	1–2		1–2	1–2	1–2	2	2	2	2–3	2	Diffuse
17.03 }	*Mn*	0												

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5520.73	...	00N	1	1		0–1	1	1	0	0		1	2	
5527.80	...	000d	00–0									00–0	0	
5529.38	*Fe*	00	0									0	0	
5531.00	*Ti*	00N	0–1	1		0	0–1	1	0–1	1	0	0–1	0–1	
5535.06	*Fe*	2	1						1–2	1		1	1	
5535.64	*Fe*	2	3–4	3–4			4	3–4	3	3		4	4	
.78	...	0												
5537.93	*Mn*	00	2	2	2	1–2	1–2	1	1–2	2	2	2	2	Diffuse
38.02	*Mn*	00												
5538.74	*Fe*	1	1–2	1–2	n. c.	1	1–2	1–2	1–2	2	1	2	1–2	Rowland's intensity poor
5546.73	*Fe*	2	2–3	2–3	2–3	2–3	2–3	2–3	2–3	2–3	n. c.	n. c.	n. c.	
5547.22	*Fe, V*	1	1–2	2	2	1–2	2	2	1–2	1–2	1–2	1–2	1–2	
5555.86	...	000	00–0		00			0	0	00		00	00–0	
.95	...	0000												
5565.70	*Ti*	00	2	2	2	1–2	1–2	2	1–2	1–2	1–2	2	2	
5573.76	...	0000	00	00	00	00	00	00	00			00	00–0	
5579.57	...	000	00–0		0	0	00	00	00	0		00	00–0	
5582.20	*Ca*	4	5	5	5	4–5	5	n. c.	n. c.	n. c.	n. c.	6	5	Winged
5583.19	...	000	00		00–0	00		00				00	00–0	
5584.73	...	000	00	00–0	0	00	n. c.	00	00	00–0	n. c.	00	00	
5586.99	*Fe*	7	8	8	8	8	8	8	9	9	8	8	8	Winged
5588.99	*Ca*	6	7–8	7	7	7–8	8	8	7	7	7	8	8	
5590.34	*Ca*	3	3–4	4	4	4	4	4	n. c.	n. c.	n. c.	n. c.	4	
5590.93	*Ti*	000	00–0		0	00–0	00–0	00	00–0	0		n. c.	00	
91.04	*Ti*	000												
5594.69	*Ca*	4	5	5–6	4–5	5	n. c.	5	5	5	5	5	5	Winged
5598.71	*Ca*	4	5	5	5	5	5	5	5	6	5	6	5	Hazy
5605.17	...	000	0	0	0	0	00	0	0	00–0		1	0	
5619.82	...	0	0–1	0–1	0–1	0–1	0–1	0–1	0–1	n. c.		n. c.	0–1	
5625.10	...	000	0	0	0	00	00	0–1		0		0	0–1	

TABLE 1—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 10	L 20	L 21	L 24	L 27	L 29	L 41	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5620.26	. . .	. .	1	1	1	0–1	1	1–2		0		1	1	Rowland gives no line here
5627.86	*V*	00	2–3	2	3	1–2	2–3	2–3		2–3	2–3	3	3	
5628.87	*Cr*	00	0–1	0–1	0–1	0	1	0–1		0–1		1	1	
5630.31	. . .	000	00–0									00–0	0	
5644.26	. . .	00	2–3	2	2–3	2	2	3		2	2	3	3	
.37	*Ti*	0												
5645.83	*Si*	1	00–0	0	0	00	0	0			0	000	00	
5646.04	. . .	00	1	1	1	0–1	1	1–2		0–1	1	1–2	1–2	
5647.40	*Ti*	00	0–1	0–1	1	0	0	0		0–1	0–1	0	0–1	
5648.80	*Ti*	00	2	2	2	1–2	1–2	2	1–2	1–2	1–2	2	2	
5651.69	*Fe*	0	0–1	0–1	1	n. c.	0–1	n. c.	n. c.	0–1	1	n. c.	1	
5654.09	*Fe*	1	1–2	1–2	n. c.	n. c.	n. c.	n. c.	1–2	1–2	1–2	1–2	1–2	
5657.67	. . .	000	1	1	1	1	1	1–2	0–1	0–1	1	1–2	1–2	
5658.10	*Y*, —	2	1–2	n. c.	1–2	1–2	n. c.	n. c.	n. c.	1–2	1–2	1–2	1–2	
5662.37	*Ti*	0	1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2	2	2	
5663.16	*Ti, Fe, Y*	1	1–2	1–2	2	2	1–2	1–2	1–2	1–2	1–2	1–2	2	
5664.80	. . .	000	0			0	00	0		0		0	0	
5665.78	*Si*	1N	0					0				00–0	0	
5668.59	*V*	000	1	1	1–2	0–1	0–1	1–2	0–1	0–1	1–2	1	2	
5669.26	. . .	1	0	0	0	0	0	0	0–1	0–1	0	0	0	
5671.07	*V*	0	3	3	3	2–3	2–3	2–3	2–3	3	3	3–4	3–4	
5672.05	*Sc*	0	2	2	2	2	2	2	1–2	2	2	2–3	2	
5675.65	*Ti*	2N	2–3	3	2–3	n. c.	2–3	3	3	2–3	2–3	2–3	3	
5680.15	. . .	000	0–1	0	0	0	0–1	1	00–0	0	1	0	0–1	
5682.87	*Na*	5	7	7	7	7	7	7	6	6	6	8	6	
5684.71	*Si*	3	1–2	2	2	2	2	1–2	1–2	1–2	2	0	1	
5687.06	. . .	000	1–2	1–2	1–2	1	1–2	2	1	1	2	2	1–2	
5688.44	*Na*	6	7	7	8	n. c.	8	6	n. c.	n. c.	7	8	7	Winged
5689.69	*Ti*	0	2	2	2	1–2	2	2	2	2	2	2	2–3	
.81	A ?	0												

TABLE I—*Continued*

ROWLAND			MEAN SPOT INTENSITY	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 40	L 43	REMARKS
Wave-Length	Element	Solar Intensity												
5690.65	*Si*	3	2–3	2	2–3	2	n. c.	n. c.	n. c.	2	2	2	n. c.	
5694.96	*Cr*	0	1	1	0–1	1	0–1	n. c.	0–1	1	1	1	0–1	
5698.56	*Fe, Cr*	1	2	2	2	2	1–2	2	2	1–2	2	1–2	2	
5698.75	*V*	1	3–4	4	4	3	3	3	3	3	3–4	3–4	3	
5700.51	*Cu?*	00	2–3	2–3	3	2–3	2	2–3	2–3	2	2	2–3	3	
5701.32	*Si*	0N	00	00	00	00–0	00	00	00	00	000	00	00	
5702.54	*Cr*	0	1	1–2	1–2	0–1	1	0–1	1	1	2	1	1	
5702.88	*Ti*	000	0–1	1	1	0	1	0–1	0	0–1	1	0–1	1	
5703.80	*V*	1	3	3	3	3	2–3	3	2–3	3	3	3	3–4	
5707.20 }	*V*	0	} 3	3	3	3	3	3	3	3	3	3	3–4	
.26 }	*Fe*	1												
5708.62	*Si*	3	1–2	2	2	2	1–2	2	2	2	1	1	1	
5709.60	*Fe*	5	7	6	7	7	7	7	8	8	6	7	7	
5712.10	*Fe*	3	5	4	5	5	5	5	4	4	6	6	5	Hazy
5713.00	*Cr*	0	1–2	1	1–2	1	1–2	1–2	1–2	2	2	1	1–2	
5714.12	. . .	000	00–0	0	00	00	00	0	0	0	0	0	0	
5716.67	*Ti*	00	2	1–2	2	2	2	2	1	1	2	2	2	
5717.92	. . .	000	00		00			00	00		00–0	00	00	
5720.67	*Ti*, A	0	1–2	1	1–2	1	1–2	2	1	1	1	1	2	
5727.27	*Ti-V*	2	3–4	3	3–4	3–4	3	3	3–4	3	3–4	4	4	
5727.87	*Cr?*	00	3	3	3	3–4	3	3	3	3	3–4	3–4	4	
5731.44	. . .	00	4	4	4	4	4	4	3	2–3	4	4	4	
5735.79 }	A	0	} 1	0–1	0–1			1–2	1	1		1	1–2	
.92 }	. . .	00												
5737.29	. . .	0	3–4	4	4	3	3–4	3	3	3	3	4	4	
5739.70	. . .	0	2	1–2	1–2	2	1–2	1–2	2	1–2	2	2–3	2	
5740.20	. . .	0	1–2	1	2	0–1	1–2	1	1–2	1	2	1–2	1–2	
5741.43	A ?	000	00–0	0		00		00		0		00		
5743.64	. . .	00	3	3	3	3	3	3	2–3	2	4	4	3	
5744.15	. . .	00	0–1	1						0	0–1	0–1	0	

TABLE I—*Continued*

Rowland			Mean Spot Intensity	L 17	L 18	L 19	L 20	L 21	L 24	L 27	L 29	L 41	L 43	Remarks
Wave-Length	Element	Solar Intensity												
5748.18	*Fe*	2	2–3	2–3	2–3	n. c.	n. c.	2–3	2–3	2–3	n. c.	2–3	n. c.	
5748.58	*Ni*	2	2–3	3	2–3	2–3	2–3	2–3	2–3	2–3	n. c.	3	2–3	
5754.88	*Ni*	5	5–6	5–6	n. c.	n. c.	6	5–6	n. c.	6	n. c.	7	6	Hazy
5760.57	*Fe*	1	1–2	2	1–2	1–2	1–2	1–2	1–2	1–2	2	1–2	1–2	
5762.48 }	*Ti*	oooNd ?	2–3	2	2	3	2–3	3	2–3	2	2	2–3	2	Widening due mainly to *Ti* line
.64 }	*Fe*	1												
5766.55	*Ti*	0	1–2	2	2	2	1–2	1–2	1–2	1–2	2	2	1–2	
5771.82	. . .	00	0	n. c.	0	0	0	0–1	0	0	0	0		
5772.36	*Si*	3	1–2				1–2	2	2	2		0–1	1–2	
5774.25	*Ti*, A	0	1–2	2	1–2	1–2	1–2	1	1	1	2	1–2	1–2	
5776.96	A, —	000	0–1		0	0	0	0			1	1	0–1	
5778.68	*Fe*	1	2	2	2	1–2	1–2	2	2	2	2	2	1–2	
5780.82	*Fe*	2	2–3	3	2–3	3	2–3	n. c.	3	n. c.		n. c.	n. c.	
5781.02 }	*Fe*	0	1	1	1	1	1	1	1	1	1	1	1	
.13 }	*Cr, Ti*	00												
5781.40	*Cr*	0	2	2–3	2	2	1–2	1–2	1–2	1–2	3	1–2	2	
5781.97	*Cr*	0	1	1	1	1	1	1	1	1	2	0–1	1	
5783.29	*Cr*	2	3–4	4	4	4	3–4	3–4	3	3	4	3	3	Hazy
5784.08	*Cr*	3	4	5	4	5	n. c.	n. c.	3–4	4	4	4	3–4	
5785.19	*Cr*	2	2–3	3	3	3	2–3	n. c.	n. c.	n. c.	3	3	3	
5785.95	*Cr*	1	2–3	3	2–3	3–4	3	2–3	2	2	2	2	3	
5786.19	*Ti, Cr*	oN	1–2	2	1–2	2	1–2	2	1	1	2	1–2	1	
5787.24	*Cr*	00	0	0	0	0	0–1	0	0–1	0		0	1	
5798.08	. . .	3	2–3	2	2	2	2–3	n. c.	2	2	2–3	2–3		
5804.48	*Ti*	0	1–2	1–2	1	0–1	1–2	1–2	1–2	1–2	1–2	1–2	1–2	
5805.99	*La*	0	0–1	n. c.	0–1	0–1	n. c.	0–1	0–1	0–1	1	n. c.		
5823.91	. . .	00	1–2	2	1–2	2	2	1–2		1	1	2		
5828.10	. . .	0	1	1	1	1	1–2	1	1	1	1			
5847.22	*Ni*	1	2	2	2	3	3	2–3	1–2	1–2	3			
5853.54	. . .	000	0	00	0	0			1	0	0			

character of these missing lines is very different in the two cases. Those absent from our list are for the greater part lines of medium or considerable intensity which appear in Mitchell's list as only slightly affected. In the case of such lines it is always difficult to be certain of a slight variation in intensity, and, while most of these lines have been observed by us, the mean variation has been too small for them to be included in the table. On the other hand, the lines present in our list and not in that of Mitchell are for the most part coincident with very faint lines in the solar spectrum, and would be classed as "band-lines" if we made use of that term.

Although the list of lines which we have given is intended rather to show the possibilities of the photographic method than to serve as a definitive table, it will not be out of place to give a brief analysis of them with especial reference to the elements to which they belong. An inspection of the table gives the following results:

TABLE II

Element	No. of Lines Affected	Mean Change of Intensity	No. of Lines Weakened
Fe	60	0.5	10
Ti	48	1.2	..
Cr	43	0.9	1
Mn	13	1.1	..
Ni	9	0.3	2
Ca	7	0.9	..
Si	7	—1.1	7
Co	6	0.3	1

Lines assigned to two or more elements	25
Blends	20
Unknown	94
Water vapor (all marked " ?") by Rowland	3
Sodium	2
Sc, La, Cu, each	1

In forming the third column of the table, which gives the mean change of intensity on Rowland's scale, care has been used in combining results for lines above 1 and below 1 in intensity, the values of the intervals being by no means the same in the two cases. For example, the change in intensity between 1 and 2 is not at all the same as between 00 and 0. A considerable number of observations was made in order to eliminate difficulty from this cause, and the results cannot be much in error so far as this source is concerned.

These observations strongly confirm Mitchell's conclusion that lines due to water-vapor are not affected in the spot spectrum. But three lines in the list are assigned by Rowland to water-vapor alone, and in the case of each of these the identification is marked doubtful.

The fact that only a little more than one-fourth of the lines in the table are "unknown" is decidedly opposed to Lockyer's view that at the period of sun-spot maximum the lines due to known elements are replaced by unknown lines. Even of this fourth a considerable proportion consists of such faint lines that their identification by Rowland would be improbable, since in the case of lines of intensity 00 on his scale an identification is much more the exception than the rule, and since the probability grows less with decreasing intensity. The evidence afforded by the iron lines is also opposed to Lockyer's conclusion. More than one-sixth of the total number of lines affected is due to that element alone, and it also enters largely into the composite and blended lines. It seems to us probable, as Cortie has suggested, that changes in the behavior of the iron lines may depend upon the character of the spots in which they occur, but at present we have by no means sufficient evidence to speak definitely on this point.

In a recent paper,[1] discussing his observations of the sun-spot spectrum in the region C to D, Fowler draws the conclusion that in the case of elements which are represented in the Sun by comparatively faint lines, such as titanium, vanadium, and chromium, the lines in the spot are strengthened in proportion to their intensities in the Sun. Our results do not support this conclusion. In the case of titanium, which is the element Fowler discusses in detail, we have, for example, in the lines λ 5566, λ 5649, and λ 5717 instances of lines strengthened from 00 to 2 on Rowland's scale. On the other hand, the stronger lines λ 5023, λ 5515, and λ 5676 are only very slightly affected, rising from 2 to 2–3 on the same scale. Perhaps an even more striking case is that of the line λ 5490, which rises from a solar intensity of 0 to 3 in the spot. This is a value that is surpassed by very few lines with a solar intensity as great as 2. Fowler remarks that "in photographs, at least, a general strengthening of all the lines belonging to an element produces a more obvious effect on the weaker lines than on the strong ones, though all may be intensified in the same ratio." This may have some effect in the case of elements with such strong lines that it is difficult to find lines in the adjoining solar spectrum of sufficient intensity for comparison purposes. In the case of titanium, however, even the strongest lines in the region under discussion are of very moderate intensity, and plenty of suitable comparison lines are available, so that it is difficult to see how much error can arise from the source which Fowler mentions.

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[1] *Monthly Notices*, **65**, 205–218, 1905.

In concluding this preliminary discussion of our results, attention should be called to the remarkable behavior of silicon, all the lines of which in this region of the spectrum, 7 in number, are much weakened. Mitchell finds a similar result for 5 lines. In view of the importance attaching to the carbon group of elements in the Sun, this result is of especial interest.

"BANDS" IN THE SPECTRA OF SUN-SPOTS

In describing the spectrum of a spot observed from April 11 to April 13, 1869, Secchi speaks of several groups of very fine lines which lie close together in the general spectrum of the Sun, but appear in spots as diffuse and nebulous lines:

> Dans la région du vert, il y en a un très-grand nombre qui deviennent très-noires dans les taches, tandis que sur le reste du disque on a beaucoup de peine à les distinguer. Ces systèmes ne paraissent cependant pas être des créations nouvelles tout à fait particulières aux taches; ils correspondent ordinairement à des raies très faibles indiquées par Kirchhoff; mais ces raies prennent dans les taches un développement extraordinaire, ce que constitue un phénomène bien tranché et complétement caractéristique.[1]

These observations, which describe very accurately the phenomena of spot bands, have received little or no mention in the literature of the subject.

In his Mount Sherman observations, Professor Young noticed between C and D in the spot spectrum some peculiar shadings terminated sharply by hard dark lines on the less refrangible side and fading out gradually in the other direction.[2] The Greenwich observations of spot "bands," which have been frequently cited, were made during the years 1880 to 1883. Many of the "bands" were only about one tenth-meter broad. On November 18, 1881, the "bands" "seemed to be composed of fine lines, but this could not be ascertained with certainty."[1] Father Cortie distinguishes three types of "bands." The first, "a certain fuzzy appearance surrounding the widened portions of the dark lines," is merely a special case of widening. The second results from increased general absorption in certain parts of the spectrum, while the third is "the appearance of real bands in the selective absorption due to a spot."[2] The lack of uniformity of the general absorption is precisely what gives rise, in our photographic observations, to the appearance of bands, and particularly to the "bands" observed at Greenwich. These are included by Father Cortie in his third class (bands proper), together with the bands observed by Professor Young at Mount Sherman. Father Cortie discusses in this paper his observations of two "bands" in the red, and remarks that "these bands or groups of lines were due to the spot alone, for no trace of them could be detected when the spot was removed from the slit, and they stand out most clearly and distinctly in the darkest part of the umbra." He concludes that bands of the third class "belong exclusively to sun-spot spectra" and are "altogether distinct from the ordinary widened or darkened or obliterated lines of such spectra." Vogel's observations of spot spectra, which may be found in the *Bothkamper Beobachtungen*,[3] include a number of bands, some of which were resolved into lines. More recent observations include those made photographically at the Yerkes Observatory in 1902,[4] and the visual results of Fowler and Mitchell, which are referred to below.

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[1] *Le Soleil*, 2d ed., **1**, 288.

[2] *Nature*, **7**, December 12, 1872.

Before citing these, reference should be made to Young's well-known resolution of the dark background of the spot spectrum into fine lines:

> But the most striking result is that in certain regions the spectrum of the spot-nucleus, instead of appearing as a mere continuous shade, crossed here and there by markings dark and light, is resolved into a countless number of lines,

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[1] *Greenwich Photographic and Spectroscopic Results*, 1881.

[2] *Monthly Notices*, **47**, 19, 1888.

[3] Unfortunately not yet in the library of the Solar Observatory.

[4] George E. Hale, "Solar Research at the Yerkes Observatory," *Astrophysical Journal*, **16**, 216, 1902.

> exceedingly fine and closely packed, interrupted frequently between E and F (and occasionally below E) by lines as bright as the spectrum outside the spot. . . . . When seeing is at the best, and everything favorable, close attention enables one to trace nearly all these lines out beyond the spot and its penumbra. But they are so exceedingly faint on the Sun's general surface that usually they cannot be detected outside the spot spectrum. . . . . Of course the resolution of the spot spectrum into lines tends to indicate that the absorption which darkens the center of the sun-spot is produced, not by granules of solid or liquid matter, but by matter in gaseous form.[1]

Dunér, in his memoir, *Recherches sur la Rotation du Soleil* (p. 12), describes his confirmation of Young's observations in the following words:

> J'ai en effet vu le spectre des taches perdant tout-à-fait l'apparence d'une bande unie plus sombre que le reste du spectre solaire, laquelle il présente dans un spectroscope d'une dispersion moyenne, et montrant de très nombreuses raies sombres, projetées sur un fond du même éclat que le spectre général du disque solaire. Ces raies ne sont pas cependant uniformément réparties et à la même distance l'une de l'autre comme les lattes d'une grille. Au contraire, on voit avec une pleine sureté, surtout en portant son attention sur les espaces qui dans le spectre solaire sont vides de toutes raies tant soit peu fortes—je cite comme exemples les lacunes 5352 . . . . 5361 et 5287,5 . . . . 5292—qu'elles sont agroupées en doublets, triplets, etc., séparées par des interstices plus larges que ceux qui séparent les raies constituantes de ces groupes. Tous les interstices, autant que j'ai pu les voir, m'ont semblé être du même éclat que ceux qui se trouvent entre les groupes des raies dans le spectre solaire. En examinant très attentivement le spectre solaire, dans le prolongement d'un tel groupe dans le spectre des taches, il m'est quelquefois arrivé de découvrir un trait nébuleux excessivement faible. En un mot: tout ce que j'ai vu, me semble prouver qu'il n'y a pas de différence fondamentale entre le spectre solaire général et celui des taches. Il est au contraire fort probable, que celui-ci se forme, pour ainsi dire, par l'exagération des caractères essentiels de celui-là, les raies excessivement faibles, presque imperceptibles, devenant parfaitement visibles, et les raies qui, dans le spectre solaire ordinaire, sont fortes devenant élargies et renforcées.

In his recent paper, "Researches in the Sun-Spot Spectrum, Region F to *a*,"[2] Walter M. Mitchell, in speaking of the resolution of the spot spectrum into fine lines, remarks:

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[1] A new line at λ 3884 ± 2, mentioned in this paper as exceedingly bright in the spectrum of a specially vigorous eruption of prominences, is very likely identical with the bright line at λ 3884.28 and λ 3884.67, in the "intermediate" and "abnormal" spectra described in our account of a remarkable disturbance of the reversing layer (*Astrophysical Journal*, **16**, 220, 1902).

[2] *Astrophysical Journal*, **22**, 4, 1905.

> The lines are most closely crowded in the region λλ 5000–5160; in the lower portions of the spectrum, particularly below D, the lines form groups rather than a uniform succession of lines as above the *b*'s. The writer doubts whether the greater part of these "band-lines" are lines ordinarily exceedingly faint in the photospheric spectrum, and brought into prominence by the vapors of the spot, but is inclined to the opinion that they are lines not present in the photospheric spectrum at all. . . . . Of course there are numerous "band-lines" that are fine and sharp, extending into and sometimes beyond the spectrum of the penumbra (long lines). These exceptional lines are undoubtedly faint lines in the ordinary spectrum.

Fowler observed two of the bands in the red described by Cortie (λ 6381.6 and λ 6389.0), and found them sharper on the red side, and not resolved into lines.[1] In the same region, however, Mitchell records seventeen groups of fine lines. Many of the bands observed by Maunder in the green were seen by Fowler, whose measures of their positions agree well with the positions determined by measurement of the photographs taken at the Yerkes Observatory. In his observations of the great sun-spot of February and March 1905, Fowler was able to observe the resolution of the continuous absorption band into lines, in spite of the comparatively small dispersion of his spectroscope.

> The general appearance of the band was very similar to that of a complex banded spectrum, such as that of sulphur, in which the maxima or "heads" are not very pronounced. Under favorable conditions, Young and Dunér were able to trace the dark components of the spot band structure in the spectrum of the disk outside the spot, but this was not clearly seen in my observations.[2]

Fowler noticed, however, that the bright gaps which occur here and there among the crowded dark lines of the "spot bands," occupy spaces between nebulous lines of low intensity in Rowland's table.

> It is accordingly not improbable that the absorbing vapor which is chiefly responsible for the darkness of a spot is thinly distributed over the general surface of the Sun, and may account for some of the very numerous faint lines of the Fraunhofer spectrum.[3]

As will be seen from the photographs reproduced in Plates IX and X, and also from the wave-lengths of the lines in the "spot-bands" given in Table III, our results completely bear out this inference. In discussing these results, the first question that arises is whether the lines in our photographs are to be regarded as identical with the fine lines observed visually by Young and Dunér. These lines were frequently seen visually by Mr. Hale in his observations of spot spectra at the Kenwood Observatory with a spectroscope not differing greatly in resolving power from the instruments employed by Young and Dunér, and subsequently by us both at the Yerkes Observatory. It may be said at once that our photographs do not show as complete a resolution of the fine lines as can be observed visually. Nevertheless, we have no doubt that the majority of the lines are shown photographically, and that the lack of more complete resolution simply arises from the fact that the linear dispersion is not great enough for the purpose. The numerous lines particularly noted by Dunér, in the above quotation from his paper, as lying in the blank regions of the solar spectrum at λ 5352–λ 5361 and λ 5287.5–λ 5292, are clearly shown in our negatives, though they may not appear in the reproductions accompanying this paper (Fig. 2, Plate IX). The best evidence, however, that the lines we have recorded represent the resolution of the "spot-bands," lies in the fact that the wave-lengths of these lines agree very closely with the wave-lengths of the very faint lines in Rowland's table. In spite of the observations of Young and Dunér, the question of the identification of the fine lines in spots with the faint lines in Rowland's table has remained unsettled, as is indicated by the fact that Mitchell expresses the opinion, in a quotation given above, that the spot lines are distinct from the faint solar lines. We have here a demonstration of one of the advantages of photography, which permits accurate measurements of the wave-lengths of such lines to be made, whereas these measurements would hardly be possible in the case of visual observations.

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[1] *Monthly Notices*, **65**, 217, 1905.

[2] *Ibid.*, p. 515.

[3] *Ibid.*, p. 516.

In spite of our identification of these fine lines of the "spot-bands" with the faint lines of the solar spectrum, we cannot subscribe to the opinion expressed by Dunér "that there is no fundamental difference between the general solar spectrum and that of the spots." If, in accordance with what appears to be his view (see the above quotation from his memoir), the spot spectrum is produced by a general increase in the intensity of the lines of the solar spectrum, no such differences in the relative intensities of the spot lines as are plainly shown in Plate IX could exist. The remarkable strengthening of some of the

PLATE IX

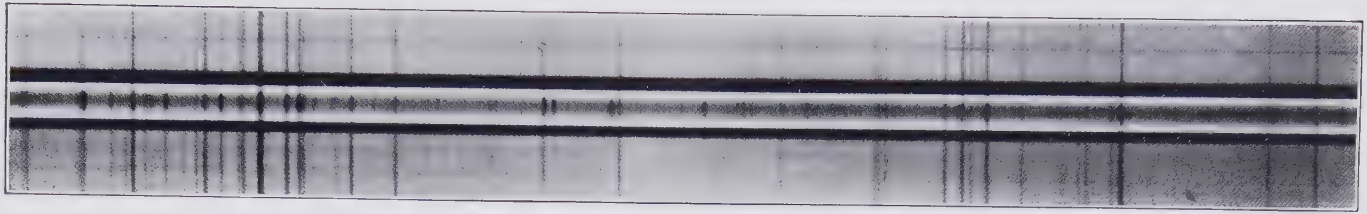

Fig. 1.—Region $\lambda 5695$–$\lambda 5775$

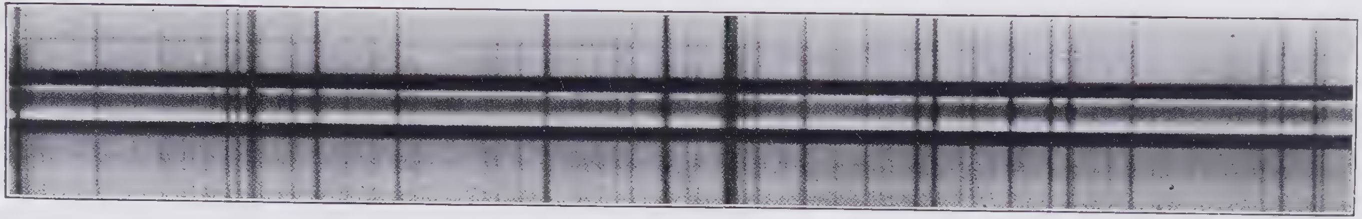

Fig. 2.—Region $\lambda 5285$–$\lambda 5365$

PLATE X

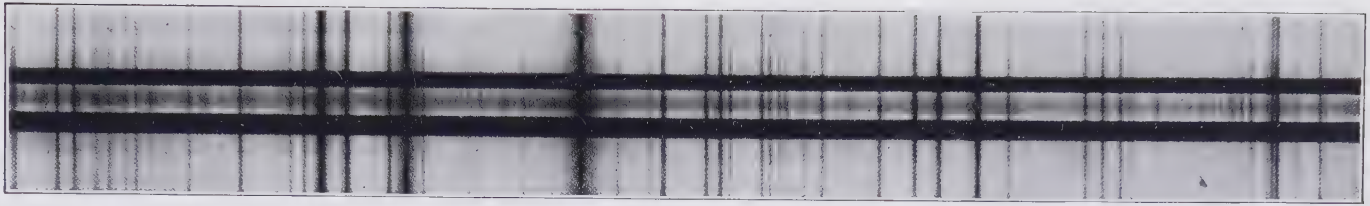

FIG. 1.—Region λ5150-λ5230

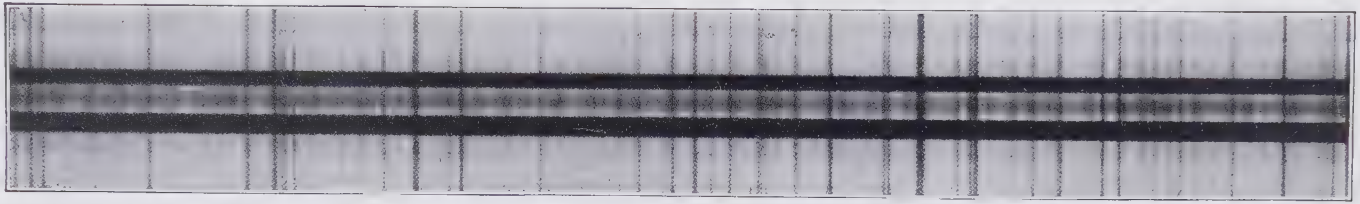

FIG. 2.—Region λ5085-λ5165

lines of certain elements, and the perhaps even more remarkable reduction in intensity of some of the lines of other elements, gives to spot spectra a very exceptional interest, and should encourage the most careful investigation, both by visual and photographic means.

Our photographs tend to confirm the view expressed by Young, Dunér, and Fowler, that the bright lines described by Young are simply interruptions in the series of dark lines, corresponding to similar interruptions in the general solar spectrum. As for the character of the fine lines in the spot spectrum, to which Mitchell calls special attention, our photographs are not as well suited as visual observations to determine a question of this kind. We hope to return to this and various other questions at a later date.

Of course, it does not follow from our discussion that true bands or flutings do not exist in the spectra of sun-spots. We can only say that we have so far failed to record them, and that many of the so-called "bands" are undoubtedly due to the fine lines shown in our photograph.

Table III contains the detailed results of Mr. Adams' measures, together with the estimates of intensity. The means derived from the separate plates are then compared with Rowland's values. The column R. – M. (Rowland – Mean) gives the differences between the wave-lengths of the lines in Rowland's table, with which we identify our lines, and our mean values, the unit being 0.01 tenth-meter. In the last column the probable identifications with Maunder's bands are added.

A considerable number of blends are included in the table. It will be seen that in almost every such case the line is noted as "broad" in the last column. These notes are taken from the original record books, and indicate that the compound character of the line is shown by its unusual width.

THE CAUSE OF THE DARKNESS OF SUN-SPOTS

In a paper with the above title,[1] Mr. Evershed expresses the opinion that the darkness of sun-spots cannot be accounted for as the result of absorption alone. He cites the explanation of Maunder that a spot may be considered as a region of high temperature, where

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[1] *Astrophysical Journal*, **5**, 244, 1897.

TABLE III

Wave-Length				Intensity				Mean		Rowland		R.−M.	Remarks
L 21	L 20	L 19	L 18	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5032.56	.54			00	00			5032.55	00	5032.56	000N	+1	These lines with 5032.09 5032.91 are Maunder's 5033.0
5033.78	.76			0	0			5033.77	0	5033.77	000 000	0	
5034.41	.42			00–0	00–0			5034.42	00–0	5034.43	000 0000	+1	Broad
5034.68	.68			00	00			5034.68	00				
5035.10	.09			00	00			5035.10	00				
5042.76				000				5042.76	000				
5043.08				0				5043.08	0				
5043.51				00				5043.51	00	5043.48	000	−3	
5044.97	.97			00	00			5044.97	00	5044.94	0000N	−3	
5046.37				00–0				5046.37	00–0	5046.38	000N	+1	
5047.14				0				5047.14	0	5047.11	000	−3	Narrow
5049.39				0				5049.39	0	5049.38	0000	−1	
5054.23				0				5054.23	0	5054.26	000	+3	Maunders 5054.7
5056.15				00–0				5056.15	00–0	5056.17	*Fe*00	+2	Maunder' 5056.7
5056.59				0				5056.59	0	5056.62	000	+3	
5059.10	.08			00	00			5059.09	00	5059.11	0000	+2	Narrow
5059.41	.44			00	00			5059.42	00	5059.41	000	−1	Maunder's 5059.2
5060.65				00–0				5060.65	00–0				
5061.56				00				5061.56	00	5061.58	000	+2	
5061.92				0				5061.92	0	5061.88	00	−4	
5063.71	.71			0–1	0–1			5063.71	0–1	5063.70	0000	−1	
5064	.03				00			5064.03	00	5064.06	0000	+3	
5065.89				00				5065.89	00	5065.89	0000	0	
5071.32				00				5071.32	00	5071.31	000	−1	
5081.76				00				5081.76	00	5081.76	000	0	
5082				0				5082	0	5081.98	000 000	−2	Broad

TABLE III—*Continued*

WAVE-LENGTH				INTENSITY				MEAN		ROWLAND		R.−M.	REMARKS
L 21	L 20	L 19	L 18	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5083.20				0				5083.20	0	5083.20	000Nd	0	
5084.80				00–0				5084.80	00–0	5084.80	000 000	0	Broad
5085.03				00				5085.03	00	5085.02	000	−1	
5086.05				00				5086.05	00	5086.08	*Cd* ?0000N	+3	Maunder's 5086.4
5086.81				0				5086.81	0	5086.79	0000	−2	
5089.38				0				5089.38	0	5089.39	000Nd ?	+1	
5090.01				00				5090.01	00	5090.00	0000	−1	Maunder's 5090.4
5090.57				00				5090.57	00	5090.57	0000	0	
5091	.48	.48	.48		00	00	00	5091.48	00	5091.48	0000	0	Narrow
5092.76	.76	.77	.77	0	0	0	00	5092.76	0				Probably Maunder's 5093.0
5092.96				00				5092.96	00	5092.98	000	+2	
5093.79	.77	.78	.76	0	0	00–0	00–0	5093.78	0				Maunder's 5093.7
5095.97	.97	.99	.97	0	0	0	0	5095.97	0	5095.95	0000 000	−2	Broad
5096.37	.40			0	00–0			5096.38	00–0	5096.36	000	−2	Maunder's 5096.2
5096		.49	.51			1	0–1	5096.50	0–1	5096.49	000 0000	−1	Broad
5100.66	.63	.63	.63	00	000	00	00	5100.64	00	5100.64	0000	0	
5101.17	.19	.19	.20	0	00	00–0	00–0	5101.18	00–0	5101.18	000 000	0	
5101.64	.63	.61	.62	00–0	00–0	00	0	5101.63	00–0	5101.66	000	+3	
5102.16				00				5102.16	00	5102.18	0000	+2	
5102.40				00				5102.40	00	5102.40	0000	+1	
5108.82	.81	.81	.84	0	00	00	00	5108.82	00	5108.80	0000	−2	
5109.26				0				5109.26	0	5109.29	000d ?	+3	
5111.16				00				5111.16	00	5111.14	0000	−2	
5111.49	.51	.52	.51	00	00	00	000–00	5111.50	00	5111.49	0000 000	−1	Broad

TABLE III—*Continued*

Wave-Length				Intensity				Mean		Rowland		R.–M.	Remarks
L 21	L 20	L 19	L 18	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5111.84	.84	.84	.87	0	00–0	00–0	0	5111.85	0	5111.85	000 0000		Broad
5112.34		.36		00		00		5112.34	00				
5112.80	.80	.80	.79	00–0	0	0	0	5112.80	0	5112.82	0000N	+2	
5114.19		.22	.21	0–1		0	0	5114.20	0	5114.20	0000N	0	
5114.70		.70	.71	0		00–0	00–0	5114.70	00–0	5114.68	000Nd?	–2	
5116.33		.27	.26	00–0		00	00	5116.30	00	5116.29	0000 0000	–1	
5116.62		.64	.66	1		0–1	0–1	5116.64	0–1	5116.64	0000	0	Maunder's 5116.9
5117.02		6.98	6.98	0		00–0	0	5117.00	0	5117.01	000 000	+1	
5118.51	.50	.51	.51	0–1	00–0	00–0	0	5118.51	0	5118.53	0000	+2	Maunder's 5118.7
5118.98	9.00	.98	9.01	1	1	0	0–1	5118.99	0–1	5118.99	000Nd?	0	
5119.52	.54	.53	.55	0	00–0	00	00–0	5119.53	00–0	5119.56	000	+3	
5119.95	.93	.93	.92	00–0	00	00	00	5119.94	00	5119.94	0000	0	
5120.26	.30	.31	.31	00	00	00	00	5120.29	00	5120.28	0000	–1	
5121.13		.10	.11	00–0		00	00	5121.12	00	5121.13	0000	+1	Maunder's 5121.0
5121.41				00–0				5121.41	00–0	5121.41	0000	–1	
5122		.39		0	0	0	0	5122.39	0	5122.37	0000 000 000	–2	Very broad
5124.67		.69	.70	0		0	0	5124.68	0	5124.70	000 00	+2	Broad
5125.73	.71	.73	.70	00	00	00	00	5125.72	00				
5126.02				00				5126.02	00	5126.01	0000	–1	
5127.11				00–0				5127.11	00–0	5127.10	0000 00	–1	Broad
5128		.72				0		5128.72	0	5128.72	000 0000	0	Broad

TABLE III—*Continued*

Wave-Length				Intensity				Mean		Rowland		R.–M.	Remarks
L 21	L 20	L 19	L 18	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5131.12				00–0				5131.12	00–0	5131.10	0000	–2	
5132.32	.34	.37	.37	0	00–0	0	0–1	5132.34	0	5132.34	0000	0	
5133.11	.09	.06	.07	00	00	00–0	00–0	5133.09	00	5133.12	000	+3	
5133.34				0				5133.34	0	5133.36	000	+2	
5134.49		.48	.47	1		0–1	0–1	5134.48	0–1	5134.50	0000	+2	
5134.79		.80	.80	1–2		1–2	2	5134.79	1–2	5134.76	000 0000	–3	Broad
5135.28		.31	.34	1		0–1	1	5135.30	1	5135.31	0000 0000	+1	
5135		.84	.82			00	00–0	5135.83	00	5135.82	000*C*, – 000*C*, –	–1	Broad
5136.65	.66	.65	.66	00–0	00	00–0	0	5136.65	00–0	5136.62	0000	–3	
5138.59	.59	.57	.57	0	0–1	0–1	0–1	5138.58	0–1	5138.60	0000 0000	+2	Broad
5138.97	.95	.96	.96	0	0	0	0	5138.96	0	5138.95	000 0000	–1	Broad
5140.46	.45	.40	.41	0–1	0	0–1	1	5140.44	0–1	5140.44	0000 0000	0	Broad
5141.45	.39	.35	.36	0–1	0–1	0–1	1	5141.40	1	5141.43	000*C*, – 0000	+3	Broad
5143.85	.83	.81	.81	1	1	0–1	1–2	5143.83	1	5143.85	000 00	+2	
5144.21	.24	.20	.20	0–1	0–1	0–1	1	5144.21	0–1	5144.20	0000	–1	
5145.93	.94	.94	.91	0	00–0	00	00–0	5145.93	00–0	5145.91	0000N	–2	Narrow
5148.91	.93	.94	.94	1	0–1	1	1	5148.93	1	5148.93	000 000	0	Broad
5149.66	.67	.68	.68	0–1	0–1	0	0–1	5149.67	0–1	5149.68	0000N	+1	
5149.97	0.01	0.00	.99	0	00–0	00–0	00–0	5149.99	00–0	5149.96	000	–3	
5150		.37	.36			1	0–1	5150.36	0–1	5150.36	00	0	

TABLE III—*Continued*

Wave-Length				Intensity				Mean		Rowland		R.−M.	Remarks
L 21	L 20	L 19	L 18	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5151.36	.36	.37	.38	00	000	000	000	5151.37	000	5151.34	0000N	−3	Narrow
5151.63	.64			000	000			5151.63	000	5151.63	0000N	0	
5152		.82	.81			00	00	5152.82	00				An unresolved band fills the space between the lines 5154.24 and 5155.30
5156		.54	.52			00	00	5156.53	00	5156.53	000	0	
5157.20	.21	.20	.21	00	00–0	0	00–0	5157.20	00–0	5157.16	0000	−4	
5157.78		.79	.81	00		0	0	5157.79	00–0	5157.78	000−,*C*	−1	
5158.51	.48	.50	.48	000	00	00	00	5158.50	00				Narrow
5158.80	.82	.82	.80	0	00–0	0	0	5158.81	0	5158.83	0000,*C*	+2	
5159.97	.96	.97	.94	0–1	0	1	0–1	5159.96	0–1	5159.95	0000	−1	
5160.39	.38	.38	.40	0–1	0	1	1	5160.39	0–1	5160.42	00N*C*,−	+3	
5163	.11	.11	.09	2	1–2	2	2	5163.10	2	5163.07	000*C*,−	−3	Very broad
5163	.79	.81	.78		00–0	0	0	5163.79	0	5163.76	000*C*,−	−3	
5168		.36	.34			00	00	5168.35	00	5168.36	000Nd?	+1	
5169	.64	.65	.69		000	000	000	5169.66	000	5169.66	0000	0	
5170	.26	.25	.25		000	000	000–00	5170.25	000	5170.27	0000	+2	
5170.74	.80	.80	.80	0	0	0	00–0	5170.78	0	5170.77	000	−1	
5171.20	.20	.21	.20	00–0	00–0	00	00–0	5171.20	00–0	5171.19	0000	−1	
5175.10	.11	.13	.14	0	00–0	00	00	5175.11	00	5175.10	000	−1	
5175.59	.54	.55	.54	0	0	00–0	00	5175.56	00–0	5175.58	000	+2	
5175.92	.93	.94	.95	00–0	00	00	000	5175.93	00	5175.92	000Nd?	−1	
5176.30	.31	.31	.31	0	00–0	00–0	00	5176.31	00–0	5176.30	000	−1	
5178.66	.69	.67	.66	00	00	00–0	00–0	5178.67	00	5178.64	000	−3	
5180		.68	.65			0	0	5180.66	0	5180.66	000 000	0	
5185		.21	.21			00	000	5185.21	000–00	5185.20	0000	−1	
5186			.53				00	5186.53	00	5186.50	000N *Fe*	−3	Broad

TABLE III—*Continued*

Wave-Length				Intensity				Mean		Rowland		R.–M.	Remarks
L 20	L 20	L 19	L 08	L 21	L 20	L 19	L 18	Wave-Length	Inten.	Wave-Length	Inten.		
5187		.64	.62			00	00	5187.63	00	5187.62	000	–1	
5190		.36	.34			0	00–0	5190.35	00–0				
5190		.74	.72			00–0	0	5190.73	00–0				Narrow
5193		.61	.61			00–0	00	5193.61	00	5193.60	0000 000	–1	Broad
5194		.14	.14			0–1	1	5194.14	0–1	5194.14	0000 000	0	Broad
5198		.51	.52			00	00	5198.52	00	5198.51	0000	–1	Narrow
5199		.79	.79	1	0	0–1	0	5199.79	0–1	5199.77	000	–2	
5201		.78	.82	00	0	00–0	00–0	5201.80	00–0	5201.77	0000	–3	
5203		.65	.67	0	0	0	00–0	5203.66	0	5203.66	000	0	
5211		.03	.02			0	0	5211.02	0	5211.02	000	0	
5212		.43	.44		0	0–1	0	5212.44	0	5212.44	000N 0000	0	Broad

the condensation of carbon (or some similar element) does not take place to the same extent as in the photospheric clouds. The diminished radiation would then be due, according to Maunder, to the lower emissive power of the gaseous contents of the spot. Evershed recognizes, however, the fundamental defect of this explanation, viz., that the radiation from a sufficient thickness of such intensely hot gas would be as great as that from a theoretical "black body," thus actually exceeding the radiation of the photospheric clouds. He endeavors to escape this difficulty by assuming that the maximum of intensity in the spectrum of this gas would be displaced into the extreme ultra-violet. The position of the maximum in the spot spectrum would then furnish the means of deciding between the two views.

Liveing and Dewar made a similar suggestion in 1883,[1] but E. Weidemann pointed out that, although the intensity of a luminous source increases most rapidly in the more refrangible region as the temperature rises, the intensity of the less refrangible region also increases.[2]

Dr. W. E. Wilson, who also believes that the darkness of a sun-spot is principally due to deficiency of radiation rather than to absorption, offers a suggestion advanced by the late Professor Fitzgerald for the purpose of getting over the difficulty. Professor Fitzgerald believed that great convection currents must exist within such a gaseous layer as that seen in a sun-spot, and that these would scatter a large amount of light, and thus prevent it from reaching the surface. Hence the effective radiation would be limited to a layer not deep enough to give the effect of a "black body," and the spot would appear dark.[3]

The evidence brought in the present paper, in addition to that previously furnished by visual observations, leaves no doubt in our minds that absorption is to be regarded as the principal cause of the darkness of sun-spots. A mere reduction of the intensity of the solar light, due to diminished radiation, could not, in our opinion, account for the observed phenomena. In describing his artificial spot spectrum,[1] Wilson states that all lines with nebulous edges are widened, while sharp lines are not affected. In answer to this, it may be said, on the one hand, that the lines which are widened in sun-spots are not all nebulous, and, on the other hand, it frequently happens that certain very faint lines are greatly increased in intensity, while other faint lines of the same element are not affected.

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[1] *Phil. Mag.*, 5th series, **16**, 402, 1883.

[2] *Ibid.*, **17**, 247, 1884.

[3] *Monthly Notices*, **65**, p. 325, 1905. Wilson, in another paper, describes an experiment in which the radiation of an arc, in a gas at high pressure, was greatly reduced by the effect of convection currents caused by suddenly releasing the pressure (*Proc. Royal Society*, A **76**, 375, 1905).

It is true that Wilson, in his recent paper, does not ascribe the widening of the lines in sun-spots entirely to the want of brightness of the gaseous layer below; he considers that the greater depth of the observed vapors of certain elements, such as titanium, whose atomic weight might determine their position between the photosphere and an underlying gaseous layer, would cause the lines of these substances to be specially conspicuous in the spot spectrum. We have already pointed out that all of the lines of such elements are not equally enhanced, but it might be said that this fact can be no more easily explained on the basis of the ordinary absorption hypothesis. We must therefore have recourse to some other test.

The necessary criterion seems to be afforded by certain determinations of the intensity of radiation of sun-spots corresponding to the light of different wave-lengths, made by Mr. Abbot on Mount Wilson during the past summer, as a part of the work of the Smithsonian Expedition. Without going into the details of these observations, which will doubtless be published in full at a later date, it may be said that the radiation of sun-spots, as compared with that of the photosphere, decreases very rapidly with the wave-length. In the infra-red the radiation of the umbra of a sun-spot is but little below that of the surrounding photosphere, whereas at the violet end of the spectrum the relative intensity of the photospheric radiation is far greater.

There can be no doubt, as von Oppolzer has pointed out, that the increase of temperature is extremely rapid in passing from the level of the photosphere toward the center of the Sun. Adopting his minimum estimate of an increase of 6000° C. for one second of arc, and applying Wien's law,[1] we find that the maximum of intensity in the spot spectrum would be shifted to a position not far from λ 2300, if the radiation were supposed to come from a region whose mean level is one second below the photosphere. Since Mr. Abbot's observations show that the maximum of intensity, which is at λ 4900 in the spectrum of the photosphere, is shifted in spots far into the infra-red, we might ascribe such a shift, whatever the source of the continuous spectrum, to the great absorption of the gases which constitute the umbra, and perhaps also to their comparatively low temperature. Leaving the question of temperature for discussion in a future paper, we may say that the radiation measures are entirely in harmony with the visual and photographic observations of spot spectra. The greatly increased absorption, shown by the marked intensity of the innumerable lines in the spot spectrum, would undoubtedly produce a decided shift of the maximum toward the infra-red. We therefore believe that the darkness of sun-spots may be sufficiently well accounted for by absorption alone.

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[1] Wilson produced a dark line spectrum by passing the light from a luminous globe through the fumes of nitrous oxide. A piece of thin paper pasted to the globe cut down the intensity of the light about 50 per cent., and its image on the slit produced a dark band in the spectrum, across which the diffuse lines were widened.

MOUNT WILSON, CALIFORNIA,
December 1905.

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[1] The equation

$$\lambda \text{ max.} \times \text{abs. temp.} = \text{const.}$$

gives 6000° C. as the temperature of the photosphere, when Abbot's value of 0.49 μ for λ max., and Lummer's value of 2940 for the constant (corresponding to a "black body") are used. If the constant is taken as 2630, determined by Lummer for platinum, the temperature of the photosphere comes out 5700° C. In computing the wave-length of the maximum for a point one second below the photosphere, we have employed these smaller values.

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SOME NOTES ON THE H AND K LINES AND THE MOTION OF THE CALCIUM VAPOR IN THE SUN[1]

By WALTER S. ADAMS

The importance of the H and K lines of calcium in the study of solar spectroscopy has been growing steadily greater within recent years. Their remarkable behavior over the general surface of the Sun, in prominences and over spots, would make them the most interesting lines in the solar spectrum even if we did not consider the fact that they are the chief, and for many instruments the only, lines which can be used with the spectroheliograph in mapping the surface of the Sun. Accordingly it may be of interest to describe some special studies on these lines which the writer has been carrying on, and to state some of the results obtained.

The spectroscope which has been employed is of the Littrow form, consisting of a 3¼-inch (83 mm) plane grating used in connection with a 4-inch (102 mm) lens of 18 feet (5.5 m) focal length. The image-forming instrument, in the case of the majority of the plates, has been a 6-inch (152 mm) lens of 62 feet (19 m) focal length, used in connection with a small coelostat. This gives an image about 7 inches (17.8 cm) in diameter. A few of the recent plates have been obtained with the Snow horizontal telescope, in which an image of the same size is formed by means of a concave mirror. When the spectroscope was transferred to the latter instrument, the modification was introduced of placing the photographic plate above, instead of to one side of the slit, with a view to making any aberration due to the slight tilting of the lens act along the lines instead of across them. The definition, which has always been excellent, seems to remain unaltered. Almost all of the plates have been obtained in the spectrum of the third order, which is bright in this grating, and sufficiently high to give full photographic resolution. The scale in this order is almost exactly one millimeter to the tenth-meter, or about the same as that of the original negatives used by Rowland in his map of the solar spectrum.

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[1] *Contributions from the Solar Observatory*, No. 6.

An accurate knowledge of the wave-lengths of H and K in the arc spectrum is essential for any investigations of these lines in the Sun, and here there seems to be considerable discordance among the values given by different observers. The best of these would seem to be:

	K	H
Rowland	3933.809	3968.617
Kayser and Runge	3933.83	3968.63
For the spark between poles of calcium:		
Eder and Valenta	3933.803	3968.638

In order to make these values comparable with the solar spectrum wave-lengths of Rowland's "Preliminary Table," the erroneous correction applied by Rowland to all of his arc standards has to be compensated. The value of this correction as given by Hartmann, after smoothing out Jewell's measures by means of a curve, amounts to −0.010 for K and −0.011 for H. The application of these corrections gives:

	K	H
Rowland	3933.799	3968.606
Kayser and Runge	.82	.62
Eder and Valenta (spark)	.793	.627

In view of these discrepancies, it seemed to me desirable to obtain some measures, and for this purpose I made a number of photographs of the H and K lines, using as a source the carbon poles of an electric arc moistened with a solution of calcium chloride, and in some cases also employing an iron terminal for the sake of the comparison spectrum. The appearance of the H and K lines produced in this way is well known, that of a sharp, narrow absorption line lying upon a strong, bright band whose width depends upon the amount of calcium vapor present. The measures were, of course, made upon the absorption line.

The first four plates were reduced with Rowland's values for the aluminium lines and λ 3973, and Kayser's value for the iron line, λ 3928. The last eight plates were reduced with the use of Kayser's iron standards wholly. As Kayser's and Rowland's systems are entirely homogeneous, this procedure is evidently quite correct. Each of the values of H and K rests upon two standard lines, and the largest value of a residual found for a standard upon any one of the plates is +0.007. The results of the measures are as follows:

	K		H
	3933.819		3968.630
	.820		.625
	.823		.631
	.820		.632
	.816		.631
	.816		.625
	.819		.629
	.815		.629
	.820		.625
	.815		.630
	.817		.629
	.818		.629
Mean	3933.818	Mean	3968.629

Applying the previous corrections to these values, we find for direct comparison with the wave-lengths of the lines in the solar spectrum:

K	H
3933.808	3968.618

The solar photographs which were measured include some which were made with the slit upon the general disk and others across spots. The approximate position of the slit upon the Sun has been noted in all cases. The narrow absorption line has always been measured, and in a considerable number of cases the bright components as well, although these measures are much more difficult. It is evident, if a is the wave-length of one of these components, and d the difference of wave-length between the absorption line and the second component, that the center of the whole bright line is given by $a+d$.

The following table contains a list of the measures. K_3 is used for the central absorption line, and V K_2 and R K_2 stand for the violet and red components of the bright line, respectively, according to the notation introduced by Hale. The plates are grouped according to the position of the slit on the disk of the Sun, whether near the center, limb, or, roughly, midway between. The method of reduction followed has been the same as that in the case of the arc spectrum measures, each line depending upon two standards. The largest residual found is less than 0.01 tenth-meter. The plates are given arbitrary numbers, and the letters following the numbers refer to separate exposures in regions of the Sun which lie close together. In a few cases different points along the lines on a single exposure have been measured, and these are denoted by figures in brackets.

MEASURES ON DISK

Plate	K_3	H_3	H_3-K_3	K_2	H_2	H_2-K_2	Remarks
			Near Center				
1 a.....	3933.797	3968.615	0.018	3933.798	3968.621	0.023	V K_2=R K_2
b.....	.809	.617	.008	.807	.620	.013	V K_2=R K_2
2 a (1)..	.805	.617	.012	.802	.616	.014	V K_2=R K_2
(2)..	.803	.620	.017	.796	.619	.023	V K_2=R K_2
(3)..	.798	.615	.017	.793	.606	.013	V K_2=R K_2
(4)..	.800	.618	.018	.796	.607	.011	V K_2=R K_2
			One-half Center to Limb				
3 a.....	.807	.622	.015	.799	.815	.016	V K_2=R K_2
b (1)..	.793	.601	.008				
(2)..	.800	.616	.016				
c (1)..	.797	.604	.007				
(2)..	.776	.588	.012				
(3)..	.815	.627	.012				
d (1)..	.806	.610	.004				
(2)..	.792	.610	.018				
			Near Limb				
4 a.....	.810	.620	.010				
b.....	.813	.620	.007	.798	.617	.019	V K_2>R K_2
5 a (1)..	.810	.626	.016	.805	.622	.017	V K_2=R K_2
(2)..	.803	.622	.019	.810	.625	.015	V K_2>R K_2
b.....	.805	.609	.004				
c......	.808	.611	.003				
6 a.....	.798	.611	.013				
b.....	.804	.609	.005				
c......	.800	.613	.013				
d.....	.801	.607	.006				

MEASURES OVER SPOTS

K_3 and H_3 Bright and Single

Near Center

7 a.....	.809	.625	.016				

Near Limb							
8 a.....	.810	.619	.009				
b.....	.815	.620	.005				
c......	.808	.611	.003				
K_3 and H_3 Dark and Narrow Near Center							
9 a.....	.806	.613	.007	.800	.606	.006	
b.....	.799	.610	.011	.789	.606	.017	
c......	.795	.603	.008	.794	.601	.007	
			0.011			0.015	

The most striking feature of these results is the general tendency toward a displacement to the violet. The average wave-length of K, for the measures on the disk, is 3933.802, and of H 3968.612, and the persistence of the direction of displacement among the separate values makes this almost unquestionably real. Taking the values already found for the wave-lengths of H and K in the arc spectrum, the average displacement amounts to 0.006 tenth-meters, which would mean a velocity of approach on the part of the calcium vapor producing the absorption lines of 0.41 kilometers a second. In taking this average, however, it is by no means intended that the conclusion should be drawn that the ranges among the separate plates are accidental. That these are due to actual differences of motion is shown not only by the fact that they considerably exceed the degree of accuracy attained in the measures, but also from a consideration of single plates, such as 3 c. In this plate we find a range of 0.039 tenth-meters for both H and K, between two points at a short distance from one another, and this is visible to the eye in a decided bending and slant of both the emission and the absorption lines. No certain evidence can be found in these observations of any such variation in the motion of the calcium vapor between the center and the limb, as might be expected from a general drift upward in a radial direction. A large amount of material will, however, be necessary before any conclusion can be drawn in regard to this matter.

The result found above, of a displacement of the absorption lines toward the violet, is opposed to Jewell's conclusion that the vapor producing these lines is descending toward the surface of the Sun. In regard to this matter, he says[1]:

> The narrow central component of the shaded lines shows a descending motion over the solar surface of the absorbing matter producing it . . . . of about a mile a second in the case of the H and K lines. The velocity in the case of the H and K lines is decidedly variable. . . . . These narrow components of the shaded lines are probably produced by meteoric matter falling into the solar atmosphere.

This contradiction of results seems to lie largely in the difference of wave-length assigned to the arc lines in the two cases. Jewell gives the values:

K	H
3933.794	3968.603

It would be of interest to know what standards were employed in the derivation of these values, but no information is given on that subject. That the choice of standards may vitally affect the results is shown by the difference in wave-length amounting to 0.013 tenth-meters assigned by Kayser and by Rowland to the iron line at λ 3928.

The results given by the emission lines, H_2 and K_2, also show a displacement toward the violet, although the measurement of these lines is much more difficult than that of the absorption lines. In this respect they confirm the conclusion formed by Jewell, although no quantitative determinations were made by him. Upon most of the plates which were measured the violet and the red components are very nearly equal; in several the violet is slightly stronger, and in one distinctly weaker than the red component. This last condition is known to be decidedly rare.

The measures given in the above table of bright K_3 and H_3 over spots show some slight indication of a longer wave-length than on the general surface. It would need a much larger number of observations to establish this, however, as the lines are wide and hazy and much more difficult to measure accurately than the absorption lines. The other measures over spots, in which K_3 and H_3 appear as dark lines between bright components, probably belong strictly to the series of measures on the disk. They were made over small spots on which photospheric light evidently encroached sufficiently to produce the characteristic appearance of the lines on the disk rather than the single bright lines which are peculiar to spots. This same effect is found in photographs of spectra of very small spots in the yellow and green region, when very little of the characteristic spot spectrum is likely to be found unless the solar definition is extraordinarily fine.

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[1] *Astrophysical Journal*, **11**, 237, 1900.

In a recent number of *Comptes Rendus*,[1] M. Deslandres states some conclusions derived by him from an examination of a number of photographs of the K line. These were obtained with his *spectrographe des vitesses*, an instrument which by means of an interesting attachment is so moved as to give on a single plate a record of a narrow strip of spectrum at a large number of successive points on the Sun's surface. In discussing these plates M. Deslandres says that at the center of the disk the two bright components of K_2 are unsymmetrical, with the red component the narrower. From this displacement of the absorption line K_3 in reference to the emission line K_2 he draws the conclusion that the vapor producing K_3 is descending, and the vapor producing K_2 is ascending. It is evident that this conclusion is by no means justifiable since the displacement of one line in reference to the other indicates only relative motion, and can have no bearing on the question of the absolute motion of the vapor giving rise to either line. The latter can be determined only from comparison with the spectrum from an artificial source, as has been done by Jewell and in this paper.

In stating that at the center of the disk the components of K_2 are unsymmetrical it appears to the writer that M. Deslandres makes too broad a generalization. In the case of each of the plates discussed in this paper which were taken at the center of the disk the components are apparently quite equal. A similar contradiction is found at the limb, where, in M. Deslandres' opinion, the lack of symmetry disappears. Two out of three of the plates which were measured show the violet component of K_2 to be decidedly the stronger. It seems probable that, while an effect like that found by M. Deslandres is perhaps to be expected, the local conditions of the calcium vapor at different points on the Sun's surface vary so much as to mask it completely in many cases. Evidence of this is found in spectra taken with a slit of considerable length; the components vary greatly at different points and often by unequal amounts.

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[1] 141, 7, 377, 1905.

One of the most important conclusions to be drawn from this series of measures is in regard to the relative wave-lengths of H and K. Rowland gives for these two lines in the solar spectrum:

K	H
3933.825	3968.625, or H−K=34.800

The values found in this investigation give the following differences:

Arc Spectrum	34.810
K_3 and H_3	34.811
K_2 and H_2	34.815

The last value is, of course, much less accurate than the others, but is certainly confirmatory of them. There is accordingly little doubt that in the Sun the relative wave-length as given by Rowland, of H as referred to K, is in error by about 0.010 units. It is, of course, equally evident that no definite wave-length can be assigned to these lines in the solar spectrum, since the vapor giving rise to them has different motions on different parts of the Sun's surface.

In considering the variations in the position of these lines as due to motion alone, the possible effect of pressure has been neglected. As Jewell has already shown, however, it is clear that the effect of pressure in the region of the solar atmosphere producing the absorption lines, K_3 and H_3, must be extremely slight. In the case of K_2 and H_2 it may be sensible, and partially compensate a still larger shift of these lines in the direction of shorter wave-lengths.

In conclusion, it ought to be stated that a very large amount of observational material will be necessary to determine the laws of motion of the calcium vapor over the surface of the Sun. Even with very powerful apparatus, the measures are delicate and complicated by the changing character of the lines. The value of such determinations toward the interpretation of spectroheliograph results will be very great, however, and similar studies on other lines, notably those of hydrogen, sodium and iron, would assist materially in determining the structure of the Sun's atmosphere.

NOTE ON H_ϵ

On a photograph taken October 27, 1904, with the slit crossing a group of small spots, the ϵ line of hydrogen appeared as a broad, hazy, bright shade across two of the spots, and a narrow bridge between them. As this is a very rare observation, measures were made on the four separate exposures upon the plate, with the following result:

$$\begin{array}{r} 3970.175 \\ .165 \\ .167 \\ .169 \\ \hline 3970.169 \end{array}$$

The agreement of the separate measures is rather illusory, the line being excessively hazy and ill-defined, as well as a full tenth-meter in width. The result agrees, however, with the value given by Rowland, which is considerably smaller than that found by most eclipse observers.

Mount Wilson, California.
November 1905.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 7
Reprinted from the *Astrophysical Journal*, Vol. XXIII, pp. 54–63, 1906

THE FIVE-FOOT SPECTROHELIOGRAPH OF THE SOLAR OBSERVATORY

By GEORGE E. HALE and FERDINAND ELLERMAN

In a recent paper[1] we have described the spectroheliograph designed for use with the 40-inch Yerkes refractor. As stated in this paper, the most satisfactory form of spectroheliograph is that in which the instrument is moved as a whole, while the image of the Sun and the photographic plate are stationary. The first spectroheliograph of this type was constructed in 1893, from Mr. Hale's general design, by Toepfer, of Potsdam, and employed in some attempts to photograph the solar corona without an eclipse, from the summit of Mount Etna.[2] In the case of the Rumford spectroheliograph, it was necessary to produce the motion of the Sun's image across the first slit by driving the telescope tube at a uniform rate in declination, the photographic plate being moved at the same time across the second slit. From a mechanical point of view, such an instrument is not an entirely satisfactory one, but the Rumford spectroheliograph has nevertheless given good photographs, some of which are reproduced in our paper.

As soon as arrangements had been made to erect the Snow telescope on Mount Wilson, it became possible to design, for use with it, a spectroheliograph of the type employed on Mount Etna. We were fortunate in having the assistance of Professor Ritchey and Mr. Pease, whose skill in working out the details of construction has been demonstrated by the very satisfactory operation of the instrument.

A photograph of the spectroheliograph, mounted for use with the Snow telescope, is reproduced in Plate XI. A better idea of the general design may be obtained from Plate XII, which shows the spectroheliograph in our instrument shop before it was completed. It consists essentially of a massive cast-iron base, bearing four short Λ-rails at its four corners, on which the moving part of the instrument is carried by four steel balls. The cast-iron platform which bears the slits and optical parts has four inverted ∧-rails which rest on the steel balls, but almost its entire weight is supported by mercury, in three tanks formed by subdivisions in the base casting. Wooden floats extend from the lower surface of the iron platform into these tanks, reducing to a minimum the amount of mercury (about 560 lbs. = 254 kg) required to bear the instrument. The motion of this platform with respect to the fixed solar image and photographic plate is produced by either one of two screws of different pitch, driven by an electric motor arranged to give wide variation in speed.

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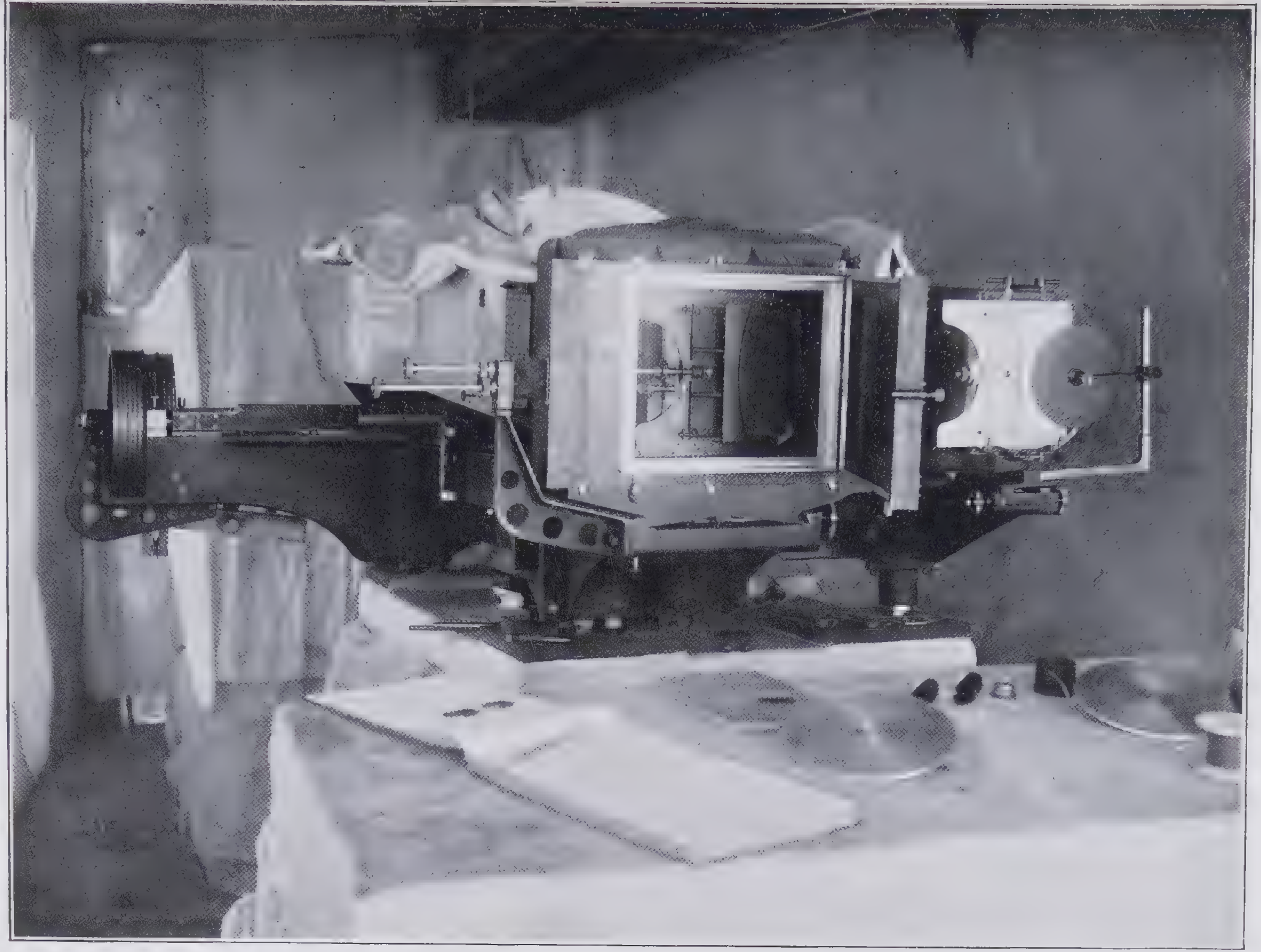
[1] "The Rumford Spectroheliograph of the Yerkes Observatory," *Publications of the Yerkes Observatory*, 3, Part 1.

[2] *Astronomy and Astro-Physics*, 13, 662, 1894.

Slits.—The first and second slits represent marked improvements over the slits employed in the Rumford spectroheliograph. They are each 8½ inches (21.6 cm) long; one jaw is fixed, and the other can be moved by a micrometer screw. The second slit can also be moved as a whole across the end of the camera, so as to permit it to be set accurately upon any spectral line after this has been brought near the center of the field by rotating a mirror in the optical train. Both slits are of very massive construction, so as to reduce the danger of flexure. The jaws are heavy castings of bronze, and the guides, in which one jaw of each pair slides, are very accurately made. The slits are so mounted that they can be rotated in their own plane by a screw, thus permitting the first slit to be placed parallel to the refracting edge of the prisms, and the second slit to be made parallel to the spectral lines. The iron castings which carry the slits can be easily removed from the collimator and camera tubes, when it is desired to substitute other slits of different curvature. The clamping screws, and the stops which determine the position angle of the slits, are so constructed that they can be released in a moment, while they define the position of the slits so accurately that no change in adjustment is required when the slits are returned to their places. The collection of slits already provided for the spectroheliograph includes one straight slit and five slits of different curvatures, required for use with either two or four prisms and for different spectral lines. Additional curved slits are constructed as the need for them arises.

The method of correcting the distortion of the solar image, which arises from the use of a straight first slit and a curved second slit



The Five-Foot Spectroheliograph Mounted for use with the Snow Telescope

is the same as that employed in the Rumford spectroheliograph: the curvature is equally divided between the first and second slits, in accordance with a suggestion made by Wadsworth some years ago. It must be borne in mind that this method is effectual only in cases where an odd number of reflections occur in the optical train (see p. 58).

It is important that the second slit should be provided with means of varying its width and changing its position when the photographic plate is in place. For example, it may be desired to make a series of photographs of the flocculi surrounding a sun-spot, corresponding to different widths of the second slit and to different positions of this slit on the H_1 band. For this purpose, as Plate XI shows, the micrometer screws are provided with extension rods, which can be turned from outside the light-tight box that incloses the plate-holder. These extension rods are furnished with micrometer heads, so that the exact position and width of the slit can be read without opening the box.

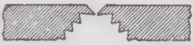


Fig. 1.—Section of Second Slit-Jaws

The jaws of the first slit are silver-plated, and when the instrument is in use a light screen of aluminium, pierced by a long narrow window, is mounted a short distance in front of this slit. Without these precautions, as our experience with the Rumford spectroheliograph showed, the heating of the jaws by the large solar image, 6.7 inches (17 cm) in diameter, would cause them to close by expansion during a long exposure.

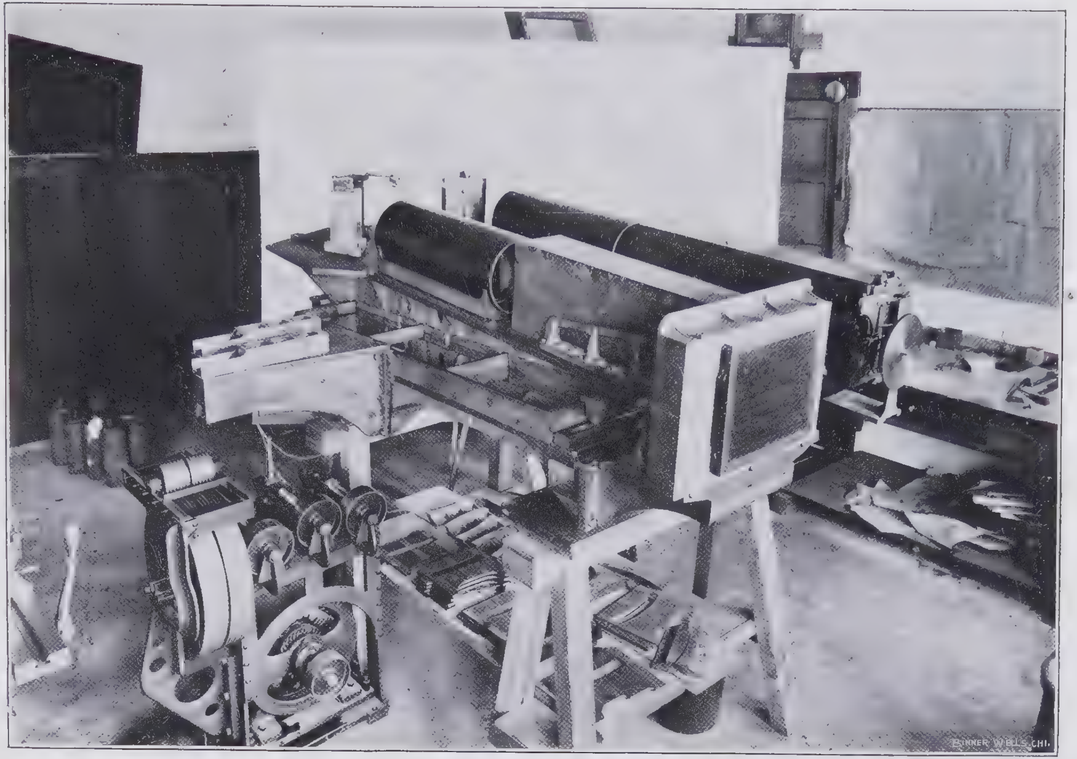
When the jaws of the second slit are of the ordinary form (beveled on the side away from the photographic plate), there is a possibility, as Mr. Evershed has suggested, that light falling on the beveled surfaces may be reflected through the jaws to the plate. In some experiments made during the past summer with a temporary spectroheliograph, the beveled surfaces were turned toward the photographic plate, to eliminate such reflections. In the present instrument a different plan has been adopted. As shown in Fig. 1, which represents the jaws in section, the lower (dead-black) surface is so formed in steps as to eliminate any possibility of appreciable reflection. In work with narrow dark lines, it is very important that all light be excluded from the plate except that which is due to the line itself. Under such circumstances the above precaution may prove of some value.

To cut off the light from the Sun's disk during an exposure on the chromosphere and prominences, circular metallic screens are provided, and mounted on an adjustable support, as shown in Plate XI. Several of these screens, corresponding to different diameters of the solar image, are available.

In order to give an accurate and rapid means of focusing the solar image on the first slit, a disk can be mounted in front of the slit, as shown in Plate XII. The support that carries this disk can be moved by a rack and pinion, and is provided with a millimeter scale, which defines its position with reference to a fixed mark. A piece of fine white cardboard is mounted on the disk, which is set in rapid rotation. By racking the whirling disk back and forth, the Sun's image (seen through dark glasses) can be very accurately focused on the white surface, which does not show such inequalities of texture as trouble the eye when an image is examined on a stationary surface. When a satisfactory focus is secured, the position of the disk is read on the millimeter scale. The distance from the zero position gives a correction by which the concave mirror of the Snow telescope can be set, with the aid of a millimeter scale attached to the rails on which it slides, so as to bring the solar image exactly in focus on the slit-jaws.

Optical parts.—The collimator and camera objectives, which are of the portrait lens type, were made by the John A. Brashear Co. Their aperture is 8 inches (20.3 cm.), their focal length five feet (152 cm). They seem to meet our specifications in every particular, including sharpness of definition, flatness of field, and equality of focal length. They can be focused from the eye-end, by milled heads, provided with micrometer scales (not visible in the photograph). The tubes, of rectangular section, which unite the first and second slits with the collimator and camera objectives, are provided with a very complete system of diaphragms, which seem to do away with all difficulty from diffuse and reflected light. The tubes of the portrait lenses themselves are also lined with diaphragms, which must

PLATE XII



The Five Foot Spectroheliograph when under Construction

be numerous in order to prevent reflection of light from the ends of the long slits.

On account of the desirability of being able to suit the dispersion employed to the work in hand, the prism-train is so designed that either one, two, three, or four prisms may be used. The prisms are of Jena glass, No. O.102, with faces $8\frac{1}{4}$ inches (21 cm) high and $4\frac{15}{16}$ inches (12.5 cm) wide. The angle of each prism is 63° 29′. The arrangement of prisms and mirrors ordinarily employed for work with the calcium lines is shown in Fig. 2. When it is desired to obtain a circular image of the Sun, two slits of equal and opposite curvature are used, and the prism-train is arranged to work with one mirror, as indicated by the solid lines in the figure. In this case, as shown by Newall, each point in the solar image will be drawn out in the direction of dispersion into a short line. Under ordinary circumstances the slits are so narrow that the distortion resulting from this cause is entirely negligible. It sometimes happens, however, that important advantages may result (in the case of the H and K lines) from the use of slits so wide that this distortion would be injurious. In such a case, a straight first slit is used with a highly curved second slit, and two mirrors are introduced into the optical train, as shown by the dotted lines. The solar image as a whole will then be distorted, but all of the points in the image will be sharp and well defined. The use of wide slits tends to decrease the contrast, but during the past summer we have obtained excellent photographs of the calcium flocculi and prominences with wide slits, which greatly reduce the exposure time.

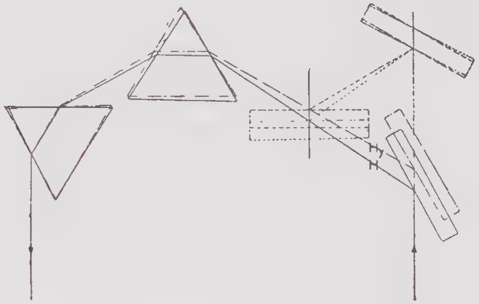


FIG. 2.—Arrangement for Calcium Lines

In order to bring any part of the spectrum upon the second slit, a mirror immediately in front of the collimator objective can be rotated from the eye-end, by means of a tangent screw. As mentioned above, the final adjustment of the line is made by moving the second slit as a whole. The two prisms are provided with a minimum deviation device, so that they may be brought at once to the position of minimum deviation for any line by setting a pointer at the corresponding reading on a scale. The mirrors may be moved parallel to the optical axis of the collimator, so as to make the light central on the prisms. The position of each mirror is given by a pointer moving over a millimeter scale. When four prisms are used, the arrangement of the train is as shown in Fig. 3. In this case two mirrors cannot be employed, but they are not needed, since the narrow dark lines used with high dispersion require the use of narrow slits.

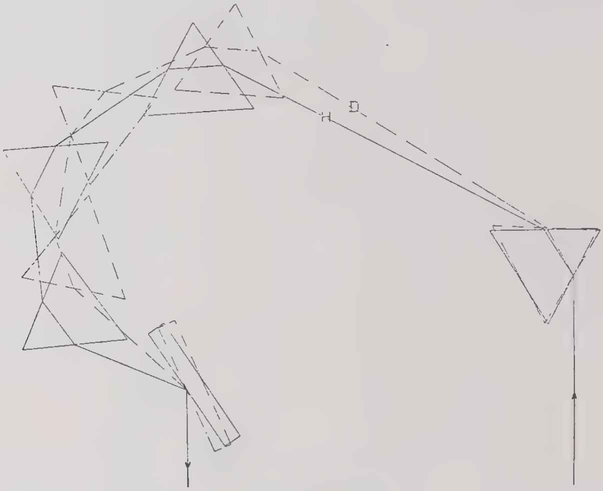


Fig. 3.—Arrangement with Four Prisms

Plate-carrier.—As shown in Plate XI, the photographic plate-holder is carried in a light box of cast aluminium, in close contact with the second slit. After the plate-holder has been inserted, the hinged aluminium cover of the box is closed and the slide drawn through a door on the side away from the first slit. This door is then closed and the entire plate-carrier moved forward by rack and pinion until a conical pin (seen in Plate XI under the iron bracket) drops into a hole in the casting on which the plate-carrier is mounted. In this position the film is almost in contact with the jaws of the second slit.

The plate-carrier is connected with the moving part of the spectroheliograph by a flexible bag, which effectually excludes the light from the plate.

When it is desired to replace the second slit with one of different curvature, the aluminium box can be removed in a moment, by turning the six buttons visible in the photograph.

The driving mechanism.—The moving platform that carries the slits and optical parts of the spectroheliograph is mounted, as already stated, on four steel balls, one inch (2.5 cm) in diameter, running in V-rails. The V's are made of hardened steel, and are ground perfectly true and parallel. As the total weight of the moving parts is approximately 1400 lbs. (636 kg), the system of mercury flotation already referred to was provided to decrease the friction on the steel balls. The result has been extremely satisfactory, the instrument moving with an ease that is surprising when its great weight is considered.

The motion of the platform is produced by either one of two screws, mounted on a strong cast-iron bracket bolted to the iron base. Both screws have hardened and ground end-thrust bearings. The finer screw is of 18 pitch, while the coarser screw, with double thread, is of 3 pitch. The long nuts are split on one side, and can thus be adjusted to take up wear. They are held between the arms of stiff bronze forks, which are connected with the moving platform by steel shafts. The shafts slide freely through cast-iron sleeves bolted to the moving platform. By inserting a conical steel pin, which passes through the sleeve and the shaft, either screw can be made to drive the platform. If neither of the two shafts is fastened to the platform, the instrument can be freely moved across the solar image by hand.

The 1 H.-P. Westinghouse direct-current motor which furnishes the motive power is mounted in a cast-iron frame, shown at the left in Plate XII. By shifting the belt of the motor, any one of three worm gears may be driven by it. Thus either of the screws that move the spectroheliograph may be driven at speeds ranging from 3 to 36 revolutions per minute. The motion is transmitted from the pulleys on the worm-gear shaft to the corresponding pulleys on the heads of the two screws by means of a series of small round belts. Braided fish-line has been found to give more satisfactory results than round leather belting. A single belt of fish-line is sufficient to drive the platform at the highest speed. In practice, however, seven belts of fish-line will be used on each pulley. The driving mechanism is mounted on a pier at some distance below the spectroheliograph,[1] and by moving the idler pulleys shown above the large driving pulleys in Plate XII, the belts corresponding to either the fine-pitch or coarse-pitch screw may be tightened, thus bringing either screw into use.

Current is supplied from a storage battery of 26 cells. The results of the preliminary work indicate that the motion will be very smooth and uniform when all the adjustments have been perfected.

The principal advantages of the new instrument over the Rumford spectroheliograph are: the larger aperture of the collimating and camera objectives, obviating loss of light at the Sun's limb; the possibility of photographing the entire disk with high dispersion; the ease of attaching slits of different curvatures; the possibility of using from one to four prisms, and either one or two mirrors in the optical train; the wide range of speed afforded by the driving mechanism; the elimination of the danger of distortion arising from imperfect synchronism in the motion of solar image and plate; and the ease of manipulation due to the general design and the improvement of details.

RESULTS

The new spectroheliograph, which has been in regular use since October 10, has already yielded some interesting results. On account of the high dispersion of the prisms, and the considerable focal length of the collimator and camera objectives, the $H\delta$ line and the line λ 4045 have been successfully used with two prisms in photographing the hydrogen and iron flocculi. Three photographs of the same region of the Sun, made on November 18, 1905, in quick succession, with the lines λ 4045, H_1 and $H\delta$, are reproduced in Plate XIII. At that time a straight first slit and curved second slit were in use,

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[1] In the preliminary work the driving mechanism has been used on a pier north of the spectroheliograph.

PLATE XIII

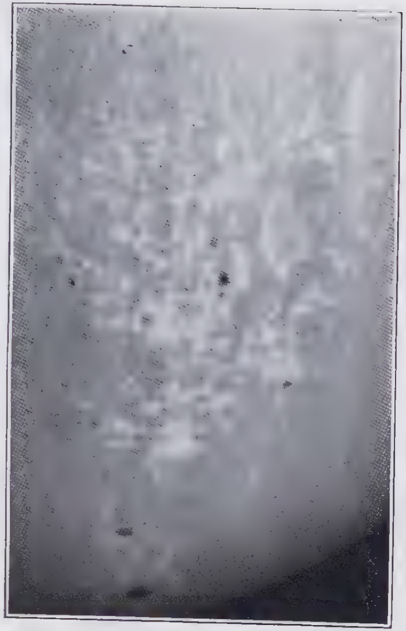

FIG. 1 —Iron Flocculi
Slit set on $\lambda 4045$

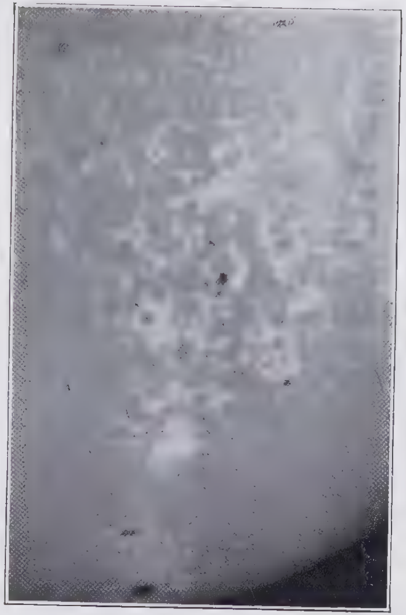

FIG. 2.—Low-Level Calcium, Flocculi
Slit set on H_1.

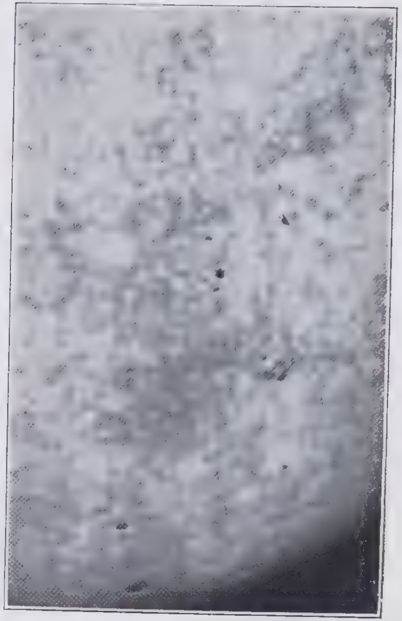

FIG. 3.—Hydrogen Flocculi
Slit set on $H\delta$

and consequently the solar image is distorted. Since the distortion is the same in all three photographs, however, they are strictly comparable with one another. It will be seen that the iron flocculi agree very closely in form with the low-level calcium flocculi. Further remarks on this subject are reserved for a future paper, which will contain the results of comparisons of iron and calcium flocculi now being made with a Zeiss stereocomparator. At present we wish to call attention to the photograph of the hydrogen flocculi, which presents some interesting features.

It will be noticed, in the first place, that the photograph confirms our results obtained with the Rumford spectroheliograph, in showing that most of the hydrogen flocculi are dark, as distinguished from the bright flocculi of calcium and iron. It will also be seen that these dark flocculi correspond roughly in form with the bright flocculi of calcium and iron, though they show certain important divergences. For example, dark flocculi may be found on the hydrogen photograph at points where no bright flocculi appear on the other plates. The H_2 (higher-level) calcium photograph, taken at the same time, also fails to show flocculi at some of these points. These differences in the distribution of hydrogen and calcium in the solar atmosphere will warrant much careful study in the future.

The most interesting feature of the hydrogen photographs, however, which was indicated to a certain extent on some of the plates taken with the Rumford spectroheliograph, is the presence of narrow bright rings, partially or completely encircling certain sun-spots. Fig. 2, Plate XIII, in our paper on the Rumford spectroheliograph, shows a neutral region in the calcium flocculi surrounding the sun-spot; for it cannot be said that this region is materially brighter or darker than the general disk of the Sun in this photograph. In our present plates, however, as may be seen from Fig. 3, Plate XIII (if the reproduction is successful), this region is in some cases distinctly brighter than the general background.

Such rings should be distinguished from the bright eruptive phenomena also frequently shown on hydrogen photographs. The bright eruptions change rapidly in form, whereas these bright rings, which are usually much less brilliant than the eruptions, do not change materially in the course of several hours. They may probably be taken to indicate the existence of comparatively hot regions in the chromosphere closely encircling certain spots. It will be a matter of great interest to study such regions in connection with other phenomena, such as the radial motion of the calcium vapor, and the intensity of radiation as measured with the bolometer. We have already convinced ourselves that the bright rings are due to hydrogen, and are not caused by any effect on the plate of light from the continuous spectrum of underlying faculæ. Indeed, the faculæ are sometimes faint or absent at the very points where the hydrogen rings are brightest.

Mount Wilson, California,
December 1905.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 8

Reprinted from the *Astrophysical Journal*, Vol. XXIII, pp. 400–405, 1906

SUN-SPOT LINES IN THE SPECTRA OF RED STARS

By George E. Hale and Walter S. Adams

In a paper on "The Spectra of Stars of Secchi's Fourth Type" (*Publications of the Yerkes Observatory*, **2**) the following statement appears on p. 129:

> The possibility that spots like those on the Sun may form a characteristic feature of fourth-type stars is strongly suggested by the evidence which we have accumulated (p. 123). It is hardly necessary to say, however, that much more evidence in this direction is needed. In view of the ease with which sun-spot spectra may be observed with instruments of moderate size, our knowledge of the widened lines is surprisingly meager. Much systematic work on spot spectra must therefore be done before the data desired for a thorough study of the question will become available. If the lines widened in sun-spots are to be regarded as characteristic of fourth-type stars, they seem to be equally characteristic of stars of the third type. This fact will permit a rigorous test of the identification of the lines to be made, since several stars bright enough to be photographed with very high dispersion occur among the stars of the third type.

Dr. Walter M. Mitchell has recently taken up this subject,[1] with the aid of his excellent observations of spot spectra, made with the Princeton refractor. He finds it almost impossible to make a satisfactory comparison of fourth-type and spot spectra, but concludes that they are not similar and that many spot lines are not represented in these stars.

The view suggested in the paper first quoted was not that fourth-type and spot spectra are similar, but rather that there was reason to suspect the presence in these stellar spectra of a considerable number of characteristic spot lines, which, if present, would presumably be due to large spots similar to those on the Sun. The presence in fourth-type spectra of strong lines and bands, such as the carbon flutings, which are known to be unaffected in sun-spots, is in no wise opposed to such a view. Indeed, these flutings are merely what may be expected to appear in a star like the Sun when it reaches an advanced stage of development.

The possibility, however, of comparing Dr. Mitchell's spot lines with those of the fourth-type stars throws new light on the subject, though it must remain in an unsatisfactory state until better photographs of fourth-type spectra can be obtained. Our five-foot reflecting telescope, when erected on Mount Wilson and provided with a suitable spectrograph, should be an ideal instrument for this research. At present we are able to contribute only such results as have been obtained with the Snow telescope, which is not adapted for work on stars as faint as those of the fourth type. So far as these latter stars are concerned, we limit ourselves for the present to recalling the probability that some of the missing spot lines in their spectra may be covered by bright lines. The rest of the evidence must stand as it is until better data become available.[1]

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[1] *Astrophysical Journal*, **23**, 211, 1906.

In order to secure material for an adequate determination of the wave-lengths of the lines in the spectrum of a third-type star, a plate of *α Orionis* was taken with the Snow telescope. The apparatus employed was a 64° prism of dense flint glass belonging to the five-foot spectroheliograph, used in conjunction with two visually corrected lenses of 5 inches (12.7 cm) aperture and 149 inches (3.78 m) focal length. The prism was sufficiently high to admit the full vertical aperture of the lenses, but in a horizontal direction could utilize a beam only 2.25 inches (5.72 cm) in width. The prism was set at minimum deviation for λ 5600. The whole instrument was inclosed in a box on the large pier inside the constant-temperature room of the Snow telescope house, and its temperature was accurately controlled by an ether regulator acting on a relay in such a way as to open and close automatically the circuit of heating coils inside the box.

It had been intended to expose the plate for two nights, but on the second night clouds cut the exposure short at the end of two hours.[2] The total exposure time was about seven hours, and the plate is not sufficiently strong to be of the best quality. It is, however, measurable from about λ 5400 to λ 5700, and the results given in the table below are derived from it. The linear scale at λ 5400 is about 1 mm = 10 Ångströms.

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[1] Of the four titanium lines referred to by Dr. Mitchell (p. 218), two are not in the "yellow region" to which my remark was limited (λ 5899.5 being beyond the reach of our three-prism plates); λ 5219.8, which was by some accident omitted from our tables of widened lines in spot spectra (*Contribution* No. 5), may be covered by a bright line in the stars (see p. 103 of our memoir); and λ 5471.4 is shown by our photographs to be one of the less conspicuous spot lines, ranging in intensity from 1 to 2.

[2] The rainy season prevented further work on the spectrum of *α Orionis*.

The estimates of intensity are based upon Rowland's scale and are subject to some uncertainty, owing to the character of the plate. Reference lines were secured by taking certain of the lines referred to by Keeler as of the same intensity in the star and in the Sun, and using Rowland's intensities for these.

RADIAL VELOCITY OF α *Orionis*

1906, February 26–27

λ in Sun	Intensity in Star	Intensity in Sun	Intensity in Spots	Velocity
5405.989	8	6	8	+53.58
5434.740	7	5	6	55.34
5447.130	8	6	8	52.19
5497.735	8	5	6	51.65
5501.683	6	5	5	54.34
5507.000	6	5	7	54.23
5569.848	5	6	6	51.75
5573.075	7	6	6	55.69
5576.320	4	4	4	55.44
5586.991	5	7	8	54.74
5624.769	4	4	4	54.38
5709.601	8	5 5	7 5	52.57

Mean	+53.82
Reduction to Sun	−27.16
Radial velocity	+26.7 km

The wave-lengths given in the following table have been corrected for radial velocity:

LINES IN THE SPECTRUM OF α *Orionis*

λ in *	λ in ⊙	Element	Int. in *	Int. in ⊙	Int. in Spots	Remarks
5393.36	5393.38	*Fe*	6	5	5-6	
5394.88	5394.84 .91	*Mn*	7	1 1	4	
5407.62	5407.59 .69	*Mn*	3	0 0	2-3	
5409.95	5410.00	*Cr*	6	4	6	
5418.99	5418.98	*Ti*?	5	1	n.c.	
5420.59	5420.51 .61	*Mn*	4	0N 0N	3	
5426.50	5426.47	——	5	00	2	*Ti*. Hasselberg has 5426.48
5432.96	5432.75 33.16	*Mn* *Fe*	5	1 2	3 n.c.	
5436.85	5436.80	——	2	1	2	Possibly *V*

LINES IN THE SPECTRUM OF *α Orionis*—*Continued*

λ in *	λ in ⊙	Element	Int. in *	Int. in ⊙	Int. in Spots	Remarks
5442.60	5442.63	*Cr*	2	00	0	
5460.74	5460.72	—	5	00	2-3	*Ti*. Hasselberg has 5460.72
5470.88	5470.80 .88	*Mn*	4	0 0	2-3	
5490.62	5490.37 90.90 91.04	*Ti* — —	9	0 0 000	3 1-2 1-2	*Ti*. Hasselberg has 5490.88
5493.67	5493.71	*Fe*	3	1	1-2	
5504.12	5504.12	*Ti*	2	0	1	
5512.92	5412.47 12.74 13.20	*Fe* *Ti* *Ca*	8	1 2 4	n.c. 3 n.c.	
5514.68	5514.56 .75	*Ti* *Ti*	7	2 2	2-3	
5517.00	5516.95 17.03	*Mn*	7	0 0	2	
5528.65	5528.64	*Mg*	7	8	n.c.	
5530.98	5531.00	*Ti*	2	00N	0-1	
5533.05	5532.97 33.09	— —	6	1 0	n.c. n.c.	
5535.65	5535.64 .78	*Fe* —	8	2 0	3-4	Rowland and Harrison have *V* line at 5535.66
5537.96	5537.93 38.02	*Mn*	3	00 00	2	
5546.82	5546.73 47.22	*Fe* *Fe, V*	5	2 1	2-3 1-2	
5565.77	5565.70	*Ti*	5	00	2	
5582.19	5582.20	*Ca*	5	4	5	
5584.77	5584.73	—	2	000	00	*V*. Rowland and Harrison have 5584.74
5594.72	5594.69 .88	*Ca* *Fe*	5	4 1	5 n.c.	
5598.67	5598.52 .71	*Fe* *Ca*	8	1 4	n.c. 5	
5626.24	—	—	3	—	1	*V*. Rowland and Harrison have 5625.27
5627.85	5527.86	*V*	4	00	2-3	
5641.67	5641.67	*Fe*	3	2	n.c.	
5644.30	5644.26 .37	— *Ti*	3	00 0	2-3	
5664.86	5664.80	—	4	000	0	
5668.63	5668.59	*V*	6	000	1	
5675.60	5675.65	*Ti*	6	2N	2-3	
5682.86	5682.87	*Na*	7	5	7	
5698.79	5698.75	*V*	7	1	3-4	
5700.53	5700.51	*Cu?*	3	00	2-3	Probably *Sc*
5703.75	5703.80	*V*	5	1	3	

The intensities of the following iron lines, which could readily be identified from their coincidence with lines in the comparison spectrum, were also noted. They were not of suitable quality for the determination of radial velocity and so were not measured.

Line	Intensity in Star	Intensity in Sun	Intensity in Spots
5397·34	10	7	9
5404·36	7	7	7–8
11.11	4	4	n.c.
15·42	6	5	n.c.
24.29	6	6	n.c.
29.91	8	6	8
45·26	5	4	n.c.
55·67 .83	6	6	n.c.
5615·52 .88	9	8	n.c.

The abbreviation "n. c." denotes that the line is unaffected.

A summary of these results gives the following values for the difference between the relative rise of intensity in *α Orionis* and spots:

RISE IN INTENSITY

	Spots	*α Orionis*	*α Orionis*—Spots
Vanadium	2.5	5·0	2.5
Titanium	1·5	4·2	2.7
Manganese	1·3	3·7	2.4

The approximately constant value of *α Orionis*—spots indicates the great similarity in the behavior of these elements in spots and in the star.[1]

Of the individual lines affected probably the most interesting case is λ 5626.24. This line does not appear in Rowland's Preliminary Table, but is prominent in spots. It is almost certainly due to vanadium, which has a line of considerable intensity at λ 5626.27. Two other vanadium lines, λ 5584.73 and λ 5668.59, of intensity 000 in the Sun, and a third of intensity 00, are all important lines in the star. The cumulative evidence afforded by the behavior of these lines as to the similarity of the spectra of stars and spots is extremely strong, quite apart from the similar testimony

[1] In comparison with these values we have for ten lines of iron affected in spots and measured in *α Orionis* the following values of the rise in intensity as referred to the Sun:

Spots	*α Orionis*	*α Orionis*—Spots
1.1	1.1	0.0

afforded by the other lines of this element, as well as those of titanium and manganese. The last-named element, as was shown by Mitchell and confirmed by the observations of Hale and Adams, is one of the most prominent in the spectrum of spots.

Though it has not been possible, on account of the character of the plate, to measure all the lines which are present, the list given above affords very strong evidence of the general agreement between the spectrum of *a Orionis* and that of sun-spots. In the region covered, λ 5393 to λ 5704, there are but four spot lines of intensity greater than 1–2 on Rowland's scale that have not been measured in *a Orionis*, and these are all present but too diffuse for measurement. Of the fainter lines, several are practically obliterated in the band, the more refrangible edge of which falls at λ 5447.

In a comparison of the stellar lines with those affected in spots the greatest interest naturally attaches to the lines of the three elements most prominent in the latter—vanadium, titanium, and manganese. Including the almost certain identifications with the lines given in Rowland and Harrison's table of the arc spectrum of vanadium, we find in the region under discussion six lines with a mean rise in intensity in spots, as compared with the Sun, of 2.5. All of these lines are found in *a Orionis* and show a mean rise in intensity of 5.0. Identifying the titanium lines in a similar way with those of Hasselberg's table, we find nine lines due solely to titanium which are affected in spots and are of intensity greater than 1–2. One of these is not measured in the star, and three others blend with adjoining lines. The remaining five have a mean rise in intensity in spots of 1.5, and in *a Orionis* of 4.2. In addition, there are two lines of mean intensity 0.8 in spots, which are measured in *a Orionis.* Of manganese there are eight lines affected in spots. Of these one is not measured in *a Orionis*, and another forms a blend. The remaining six show a mean rise in intensity in spots of 1.3, and in *a Orionis* of 3.7.

As Lockyer has pointed out, the appearance of characteristic spot lines in stellar spectra may indicate a similarity of the physical conditions in sun-spots and in these stellar atmospheres, rather than the presence in these stars of spots like those on the Sun.

SOLAR OBSERVATORY,
Mount Wilson, May 1906.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 9

Reprinted from the *Astrophysical Journal*, Vol. XXIV, pp. 129–132, 1906

LATITUDE AND LONGITUDE OF THE SOLAR OBSERVATORY

By GEORGE E. HALE

Through the courtesy of Superintendent O. H. Tittmann, of the United States Coast and Geodetic Survey, the astronomical latitude and longitude of Mount Wilson were determined in December 1905 and January 1906 by Assistants Edwin Smith and John E. McGrath, of the Survey. I am indebted to Superintendent Tittmann for the following information regarding the observations.

The latitude observations were made on three nights—December 24, 27, and 29, 1905. Forty-six observations were taken on sixteen pairs. The observations were made with meridian telescope No. 3, having a focal length of 80 cm and a clear aperture of 7 cm. The value of one 2-millimeter division of its latitude level is 1.″186, and the value of one turn of the eyepiece micrometer, as determined from the latitude observations at this station, is 65.″034. The probable error of a single observation, as derived from the residuals of the separate observations on each pair from the mean result for that pair, and, therefore, not including the errors of the star places, was found to be ±0.″36. The mean result from each pair is given in Table I. The star numbers, as given in this table, refer to the *Greenwich Ten Year Catalogue* of 1880, with the exception of the two numbers which are inclosed in parentheses; these refer to the *Greenwich Ten Year Catalogue* of 1890. The declinations of nineteen of the stars observed depend upon computations of mean declinations, based upon many catalogues, made at the Survey Office on the Boss system in former years in connection with other latitude observations. For the remaining thirteen stars, for which sufficiently accurate declinations were not available at the Survey Office, Professor Lewis Boss kindly furnished the mean declinations from the manuscript of his *Preliminary General Catalogue* now being prepared under a grant from the Carnegie Institution.

TABLE I

Recapitulation by Pairs of Results for Latitude (Mount Wilson, California, 1905)

Pairs. No.	Star Nos. Gr. 10-Year 1880		Latitude	No. Obs.	*W*	*V*
1	179	191	34° 12′ 55″.10	3	15	−0″.03
2	234	(557)	55.01	3	11	+0.06
3	260	269	55.72	3	18	−0.65
4	282	321	54.83	3	16	+0.24
5	327	340	54.97	3	15	+0.10
6	362	389	54.57	3	9	+0.50
7	401	414	55.23	3	18	−0.16
8	(935)	431	55.22	2	11	−0.15
9	465	475	55.09	3	16	−0.02
10	490	500	55.62	3	16	−0.55
11	520	551	54.98	3	17	+0.09
12	557	563	54.48	3	7	+0.59
13	604	612	54.90	2	11	+0.17
14	621	662	54.57	3	13	+0.50
15	679	700	54.64	3	13	+0.43
16	719	735	55.34	3	16	−0.27

The computation of the latitude was made in accordance with Appendix 7 of the *Coast and Geodetic Survey Report* for 1898, and the weights were assigned to separate pairs by the method indicated at the bottom of page 362 of this Appendix. The weighted mean value for the latitude of the station of observation is 34° 12′ 55″.07 ±0″.06. The reduction to sea-level to take account of the curvature of the vertical is 0″.28, making the reduced latitude of the point of observation 34° 12′ 54″.79.

The observations to determine the difference of longitude of Los Angeles and Mount Wilson were made on six nights: December 31, 1905; January 2, 3, 4, 7, 8, 1906, by Assistant John E. McGrath at Los Angeles with transit No. 19, and Assistant Edwin Smith at Mount Wilson with transit No. 18. A description of these instruments is given on page 268 of Appendix 7 of the *Report* for 1898, with an illustration opposite page 320. Each instrument has been fitted with a transit micrometer of the type described in Appendix 8 of the *Report* for 1904, "A Test of the Transit Micrometer."

The difference of longitude Los Angeles—Mount Wilson is the first one wholly within the United States determined by using transit micrometers. Earlier in the season the transit micrometers were used in observations to determine three differences of longitude fixing three points in Alaska. The observations on each night at Los Angeles and Mount Wilson consist of two time sets, each involving ordinarily twelve stars; one time set being taken before the exchange of signals between stations by telegraphy, and the other afterward. The observed differences of longitude on each night are shown in Table II, together with the residuals, the mean and its probable error.

TABLE II

DETERMINATION OF DIFFERENCE OF LONGITUDE OF TRANSIT INSTRUMENTS AT LOS ANGELES AND MOUNT WILSON, CALIFORNIA

Date	Difference of Longitude	Residual
1905, Dec. 31	$0^m\ 47^s.580$	$-0^s.009$
1906, Jan. 2	.601	$-$ .030
3	.561	+ .010
4	.608	$-$ .037
7	.532	+ .039
8	.544	+ .027
	Mean $= +0^m\ 47^s.571 \pm 0^s.008$	

The longitude of the transit of 1892 at Los Angeles is $7^h\ 53^m\ 01^s.561$, fixed by the adjustment of the longitude net of the United States, see Appendix 2 of the *Report* for 1897. The transit used by Assistant John E. McGrath was $0^s.140$ west of the transit of 1892, and its longitude was therefore $7^h\ 53^m\ 01^s.701$ Applying to this the measured difference of longitude, as given in Table II—namely, Mount Wilson transit east of Los Angeles transit $47^s.571$—there is obtained as the longitude of the transit at Mount Wilson $7^h\ 52^m\ 14^s.130 = 118^\circ\ 3'\ 31''.95$.

The transmission time, as determined on different nights, varied from $0^s.003$ to $0^s.010$, with a mean of $0^s.007$.

The local triangulation at Mount Wilson, done by Assistant Edwin Smith, shows that the Mount Wilson triangulation station is $4''.93$ north and $13''.59$ west of the Mount Wilson longitude station, and that the Snow Telescope Pier is $4''.74$ north and $2''.94$ west of the Mount Wilson longitude station. Hence the astronomical position transferred to each of these points is as follows:

MOUNT WILSON TRIANGULATION STATION

Latitude	$34^\circ\ 12'\ 59''.72$
Longitude	$118\ \ 3\ 45.54$

Snow Telescope Pier

Latitude	34° 12′ 59″.53
Longitude	118 3 34.89

By comparing the astronomical latitude and longitude, as given in this report, with the geodetic position of the Mount Wilson triangulation station on the United States Standard Datum, as printed on page 541 of Appendix 9 of the *Report* for 1904, "Triangulation in California," it is found that the astronomical latitude is 26″.50 less than the geodetic and the astronomical longitude is 5″.63 greater than the geodetic. The deflection in the prime vertical at the Mount Wilson Longitude Station is therefore moderate in magnitude, but the deflection in the meridian is very large; one of the largest, if not the largest, yet observed in the United States.

I take pleasure in extending the hearty thanks of the Solar Observatory to Superintendent Tittmann, and to Messrs. Smith and McGrath, for their kindness in undertaking this work, which was carried out with the precision and dispatch characteristic of the Coast and Geodetic Survey.

Solar Observatory,
Mount Wilson, California,
June 1906.

PLATE XIV

Contributions from the Solar Observatory of the Carnegie Institution of
Washington, No. 10

Reprinted from the *Astrophysical Journal*, Vol. XXIV, pp. 61–68, 1906

THE SPECTROSCOPIC LABORATORY OF THE SOLAR OBSERVATORY

By GEORGE E. HALE

An important requirement in the programme of research of the Solar Observatory is met by the provision of a spectroscopic laboratory, adequately equipped for the investigation of such physical and chemical phenomena as may be encountered in connection with our solar and stellar observations. It will only occasionally happen that data required to explain the results obtained with the solar spectrograph and the spectroheliograph are already available in spectroscopic literature. The Zeeman effect, for instance, has been recorded in the case of comparatively few lines, so that without additional observations it could not be determined whether certain lines which vary together in the Sun, also behave alike in a magnetic field. Displacements due to pressure must frequently be known in connection with measurements of lines in the solar spectrum, but the required values are only occasionally found in published papers. The same may be said of the effects of change of temperature, of potential, of self-induction, of current strength, of the influence of the gaseous atmosphere in which the luminous source is placed, etc. It is evident that what is essential, in case the results constantly encountered in both solar and stellar work are to be interpreted without delay, is a collection of light-sources so designed and arranged that the effect of any of the above mentioned variables can be observed with spectroscopes of any desired resolving power.[1] It is not so much a question of the saving of time, which the provision of these means undoubtedly offers, as it is of the greatly increased efficiency of the working programme thus rendered possible. The immediate imitation in the laboratory, under experimental conditions subject to easy control, of solar and stellar phenomena, not only tends to clear up obscure points, but prepares the way for the development along logical lines of the train of reasoning started by the astronomical work. It is a question, then, of equipping the laboratory in such a way that its various resources may be effectively utilized at any time, and without the delays ordinarily experienced when apparatus must be specially prepared for a certain investigation. In the desired plan the apparatus must be always ready, needing only the operation of a switch or the adjustment of a mirror to bring it into action.

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[1] As an illustration of this it may be remarked that in our study of sun-spot spectra the following light-sources have been employed: ordinary arc, in air, hydrogen, and CO_2; rotating arc, at low and high pressures; synchronous arc; spark in air; spark in water; oxyhydrogen flame; electric furnace.

In the spectroscopic laboratory of the Yerkes Observatory I first tried the principle which has been more fully developed in our spectroscopic laboratory on Mount Wilson. The various light-sources, including an ordinary arc in air, a spark in air, a spark in liquids, and a spark in compressed gases, were arranged on the circumference of a wooden table, having at its center a plane mirror capable of rotation about a vertical axis. By means of this mirror, set at the proper angle, light from any one of the sources was reflected to a concave mirror which, in its turn, formed an enlarged image of the light-source on the slit of a concave grating spectrograph.

At the Solar Observatory the apparatus is arranged as shown in Plate XIV. Instead of a circular wooden table, an annular concrete pier is employed, giving space on the inner wall for the various switches used to control the current supplied to the different sources, and also permitting the observer to inspect any light-source from the direction of the plane mirror at the center of the pier. Instead of a single plane mirror, two are provided, capable of rotation independently of one another, about the same vertical axis. By means of divided circles, the azimuth of either mirror can be read. When the Littrow spectrograph[1] is in use, only the lower plane mirror is employed. By setting this at the proper angle the light from any one of the sources can be sent to the concave mirror (seen near the the middle of Plate I), which forms an image of the source on the slit of the Littrow spectrograph. If the one-prism quartz spectrograph, the interferometer, or the echelon spectroscope is to be used in place of the Littrow spectrograph, for the study of the light-source, the concave mirror is tipped back at a small angle, so as to return the light to the upper plane mirror, from which it is reflected to the slit of one of these instruments. In Plate XIV the quartz spectrograph may be seen just above the concave mirror. To the right of this is a Hilger one-prism spectroscope, which provides a monochromatic beam for observation with the interferometer (shown in position near the spectroscope), or with the echelon spectroscope, which stands on the right of the pier that carries these instruments. This pier is separated from the annular pier by a space through which the observer may pass.

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[1] The rectangular box which carries the slit and plate-holder of this instrument is shown on the pier at the left of Plate I.

The various analyzing instruments, with which the light-sources are studied, may be briefly described as follows:

1. A direct-vision spectroscope by Jobin, for the preliminary visual examination of spectra.

2. A Fuess quartz spectrograph, with collimator of 3.8 cm aperture and 81.3 cm focal length, and camera of the same aperture and focal length. This instrument has a double Cornu prism of quartz, and a Zeiss prism of ultra-violet glass, to be used if somewhat higher dispersion is desired. The spectrograph is provided with means for photographing a series of narrow spectra on a single plate, and is used for preliminary and for qualitative studies, especially in the ultra-violet.

3. A Littrow spectrograph of 12.5 cm aperture and 3.72 m focal length. The combined camera and collimating lens is by Brashear, and is corrected for work in the visible spectrum. The plane grating, by Michelson,[1] has a ruled surface 8.3×4.4 cm, with 7,000 lines to the cm. It may be used in any order, by setting it at the proper azimuth. The slit is mounted immediately above the photographic plate. The plate-holder can be raised or lowered, so as to permit several spectra to be photographed on a single plate.[2]

4. A Michelson interferometer (not shown in the plate), for the analysis of spectral lines, the determination of absolute wave-lengths and the measurement of lengths. This instrument receives mono-

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[1] We are indebted to Professor Michelson for the use of this excellent grating, which is one of the first products of his new ruling engine.

[2] This temporary instrument will be replaced by a permanent one of 5.5 m focal length.

chromatic light from a one-prism spectroscope by Hilger, provided with a prism of special form, from which the beam emerges at an angle of 90° with the axis of the collimator. Different parts of the spectrum can be brought to the slit of the interferometer collimator by rotating the prism. The same spectroscope can be used in connection with a Pérot-Fabry interferometer or with an echelon spectroscope.

5. A Pérot-Fabry interferometer by Jobin, exactly similar to the instrument used by Messrs. Pérot and Fabry for the determination of absolute wave-lengths and the analysis of spectral lines.

6. A 33-plate echelon spectroscope by Hilger, with plates 15 mm thick. This instrument is used in studies of the Zeeman effect, and other work requiring the highest obtainable resolving power. The slit can be opened or closed from the eye-end, or moved entirely out of the way when a spectral line is being picked out for observation. In the latter case the echelon is moved to one side and the image of the spectrum, formed by the auxiliary spectroscope in the focal plane of the collimator of the echelon spectroscope, is seen with the observing telescope. Provision is made for using the echelon at 90° from its ordinary position, as Nutting has done, for the purpose of separating the overlapping spectra. For spectra having but few lines it is sometimes advantageous to remove the prism from the auxiliary spectroscope and insert it beyond the echelon. When this is done the observing telescope stands at 90° with the axis of the echelon, as shown in Plate XIV.

The following apparatus stands on the annular pier: The first instrument on the right is a DuBois magnet of Hartmann & Braun's larger model, for studies of the Zeeman effect. It is mounted on a base in such a way that it can be rotated through an angle of 90°, so that light from the source can be observed parallel or at right angles to the lines of force. A bismuth spiral is provided for measuring the strength of the field. In the illustration a mercury tube is hung between the poles of the magnet, and connected by heavy pressure tubing with the Geryk duplex vacuum pump shown on the wooden table at the right. The magnet requires a potential of 64 volts, which is supplied from a storage battery in an adjoining building. The vacuum pump, which is supplied with a McLeod gauge by

Müller-Uri, is driven by a small electric motor. A transformer of 600 watts capacity, giving from 6,000 to 10,000 volts, is used to illuminate the mercury tube. This is supplied with an alternating current from the generator in the power house. In connection with the transformer there are provided a condenser of variable capacity, and a coil of variable inductance.

Just beyond the magnet may be seen the apparatus for the study of the spark spectrum in air, at atmospheric pressure. The metals to be investigated are held by a pair of clamps in the lower set of terminals. The upper terminals are in series with the lower ones and serve as an auxiliary spark-gap. An electric fan, blowing a strong current of air upon the two sparks, prevents arcing and undue heating of the poles.

To the left of the air spark stands the apparatus for the study of the spark spectrum in water and other liquids. This consists of a strong iron case, into which the horizontal terminals are led through long corrugated cylinders of vulcanite. Glass windows, in the front and rear of the case, permit the spark to be seen from either side. The metals to be investigated are turned or ground into the form of small rods, and are mounted in brass caps, which can be screwed as terminals to the rods passing through the vulcanite cylinders. These rods are threaded, permitting the distance between the terminals to be varied at will. As the poles are rapidly consumed during the passage of the spark, it is necessary to adjust the distance between them while the exposure is in progress. For this purpose a gear is attached to the rod carrying one of the terminals (the left one in the illustration), and this can be turned by means of a pinion at the inner extremity of a long ebonite handle, mounted on a conical ebonite support attached to the iron case. By this means the distance between the poles can safely be controlled, even when a transformer giving 64,000 volts is employed. When water is used it is kept circulating through the tank during the exposure, entering by means of a rubber tube near the bottom of the tank, and passing out through a rubber tube at the top. An auxiliary air-spark, blown out by the electric fan, is always used in series with the water-spark. The voltage, self-induction, capacity, etc., of the discharge circuit can be varied as desired. A tight-fitting iron cover is provided for the tank, in case high liquid pressures are to be used.

To the left of the central plane mirrors may be seen the ordinary arc, for experiments at atmospheric pressure with carbon or metallic poles. This arc is provided with an automatic regulator, so constructed as to keep the poles well separated during the exposure. By means of a suitable rheostat, the current through the arc can be varied as desired. Important differences in metallic spectra are obtained by the use of currents of 2 amperes and 30 amperes respectively, the difference of potential between the poles remaining the same in each case. Direct current of any desired voltage, up to 110, is applied to this arc from a storage battery, and alternating current, of one, two, or three phase, from the generator in the power house.

The next light-source on the pier is a synchronous rotating arc designed by Professor Crew, and constructed for us under his kind supervision. It consists of a small alternating motor, with a device for bringing it into synchronism with the single phase alternating current from our generator. By means of a position circle the rotating metallic electrode can be set at any desired angle, so as to permit the arc to be observed at any phase from 0° to 90°. The fixed electrode is adjustable by means of a hand-screw. The interesting variations in arc spectra obtained by varying the phase have been described by Professor Crew in the *Astrophysical Journal.*[1]

Next to the synchronous arc stands the pressure arc, for the study of the low potential discharge (up to 110 volts, direct or alternating current) in various gases at low and high pressures. This apparatus was constructed by Gaertner. The rotating arc is viewed through a window in the front of the case. One of the electrodes can be adjusted, if necessary, during the exposure. Pressures up to 60 atmospheres are supplied from cylinders of liquid CO_2, obtained in Los Angeles. For higher pressures a special pump, kindly designed by Mr. Petavel of the University of Manchester, and constructed under his supervision by Charles W. Cook, the University instrument maker, will soon be installed. For low pressures the Geryk pump is used.

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[1] 22, 199–203, 1905.

All investigation on the details of the solar image are made with the Snow telescope. Sunlight is nevertheless frequently required in the laboratory for comparison spectra, etc., and is supplied by the Fuess heliostat shown on the shelf outside the window, on the right of the plate.

The switch-board, with connections to the power house and storage battery, is shown on the left of the plate. Ammeters and voltmeters for direct and alternating current are provided. A large 5 K. W. transformer, specially built by the Peerless Electric Company, giving 1,000, 2,000, 4,000, 8,000, 16,000, 32,000 or 64,000 volts, will soon be installed.

A Ducretet coil, giving a 35-cm spark, with rotating mercury interrupter, has recently arrived. This will be used for various purposes, and with an X-ray tube for certain investigations on ionization. A sensitive radiometer, built by Gaertner, and fitted by Professor Nichols with a suspension system which he was kind enough to make for us, is also available.

Our recent study of sun-spot spectra has made it necessary to supplement the above equipment with a Moissan electric furnace, of 50 K. W. capacity. This is being installed, with a large Littrow spectrograph, in our Pasadena laboratory, since the power plant on Mount Wilson cannot supply sufficient current. The 5 K. W. high-potential transformer will also be used for the present in Pasadena.

It is not the purpose of this article to describe in detail the other rooms of the laboratory, which include a plate-measuring room, with a stereocomparator and other measuring machines for the study of photographs of spectra and spectroheliograph plates; an enlarging room, with cameras for use with skylight or electric arc; two photographic dark rooms; a clock room, containing a Riefler mean time clock, with nickel-steel pendulum, which controls electrically a mean time clock in the Snow telescope house; a small chemical laboratory, etc. The laboratory is heated by steam and lighted by electricity.

Solar Observatory,
Mount Wilson, California
July 1906.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 11

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PRELIMINARY PAPER ON THE CAUSE OF THE CHARACTERISTIC PHENOMENA OF SUN-SPOT SPECTRA

BY GEORGE E. HALE, WALTER S. ADAMS, AND HENRY G. GALE

In considering the characteristic features of the spectra of sun-spots, three points especially attract attention:

1. The fact that certain lines in the spectrum of a given element are strengthened, while others are weakened; the remainder of the lines being unaffected.

2. The inclusion of all the strengthened lines within the visible spectrum, none of them occurring in the ultra-violet, and their predominance in the red, yellow, and green.

3. The relatively great intensity of the continuous background[1] of the spot spectrum in the less refrangible region.

From our general knowledge of spectra corresponding to various temperatures we are aware:

1. That in passing from a high temperature to a lower temperature, certain lines are relatively strengthened, some are unaffected, and others are diminished in intensity.

2. That such a reduction of temperature is accompanied by an increase in the relative intensity of the less refrangible lines, and a shift of the maximum of a continuous spectrum toward the red.

The general correspondence of these two groups of facts led us to seek for an explanation of the spectra of sun-spots, on the hypothesis that the metallic vapors within the spots have a temperature lower than that of the photosphere.

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[1] Careful visual observations of the spot spectrum have been made with the Littrow spectroscope of 18 feet (5.5 m) focal length in the third and fourth orders of a 4-inch (10 cm) grating, having 14,438 lines to the inch (5,672 to the cm). Although an immense number of fine lines can be seen in the spot spectrum, they nevertheless seem to lie on a continuous dark background, which we have not been able to resolve into lines. This background, however, is interrupted at certain points by lines or breaks, which seem to be nearly as bright as the spectrum of the adjacent photosphere. They do not appear to us like genuine bright lines, and we are unable to offer an adequate explanation of them, unless the dark background is resolvable. Up to the present time we have observed none of the bright reversals (narrow bright line on wider dark line) of spot lines described by Mitchell, although the high resolving power of our spectroscope should render such reversals easily visible.

Fortunately, the best of material was available for the investigation. Photographs of spot spectra, made with the Snow telescope and the Littrow spectrograph of 18 feet (5.5 m) focal length, show an immense number of affected lines.[1] These plates, which cover the region from D to $H\beta$, have been supplemented by photographs of the entire spectrum of recent large spots, extending from A in the red to the ultra-violet, made by Mr. Ellerman. Plates extending into the ultra-violet, which had previously been used for a study of the H and K lines, were also available.

The laboratory work began with a study of iron and other metals in a synchronous rotating arc, designed by Professor Crew, and constructed for us under his supervision. This ingenious instrument permits the spectrum of the alternating arc to be photographed at any desired phase. In an account of his experiments with the arc, published last year in the *Astrophysical Journal*, Professor Crew showed that the changes in the relative intensities of lines photographed at phase angles varying from 90° to 0° correspond to the changes observed in passing from high to low temperatures. The arc gives excellent results, but the brightness decreases rapidly with the phase, involving an undesirable increase of exposure time. It therefore occurred to Mr. Gale to try the effect of varying the current strength in an ordinary 110-volt direct current arc, the difference of potential between the poles being kept approximately constant. Spectra photographed with currents of 30 amperes and 2 amperes respectively show changes of intensity similar to those observed with the synchronous arc, with the advantage that the spectrum given by the arc with low current requires a much shorter exposure than that of the low-phase synchronous arc, which is necessarily intermittent. We have thus photographed, with currents of 30 amperes and 2 amperes, the spectra of iron, titanium, vanadium, chromium, manganese, calcium, and other metals characteristic of sun-spots. As the work progressed a correspondence was observed between lines that are "enhanced" in the spark and those that are weakened in sun-spots. For the further study of this effect we have also photographed the spectra of the same elements in the discharge of a 600-watt transformer, giving about 6,000 volts at the secondary terminals. A condenser was used in the discharge circuit, and the potential was increased by an auxiliary air spark, in series with the observed spark, both being exposed to a strong blast of air from an electric fan. Under these conditions the "enhanced"[1] lines of the spark are well shown in the photographs. We are about to investigate them more effectively with the aid of a 5 K. W. transformer, giving 1,000, 2,000, 4,000, 8,000, 16,000, 32,000, or 64,000 volts, as desired.

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[1] For a partial list of the strengthened lines see *Astrophysical Journal*, **23**, 11, 1906.

The instrument with which by far the greater part of the laboratory spectra used in this investigation have been secured is a grating spectroscope in the Littrow form, of 13 feet (3.96 m) focal length. The grating is by Michelson, with 700 lines to the millimeter, and gives a bright first-order spectrum on one side with excellent definition. The slit is provided with an occulting bar, by means of which two spectra that are to be compared can be photographed in the usual way. In most of this work, however, we have preferred to make the separate exposures through the same window in the bar, moving the plate between exposures. In this way we have been able to obtain a greater range of exposure time, and the arrangement has proved satisfactory, since the slight displacements between the separate spectra are of no consequence for our purpose. The window used has a diameter of about 1.2 mm. Our usual procedure in comparing the weak and the strong arcs has been to place on each side of the weak arc spectrum two spectra of the strong arc, giving different exposure times in the two cases. From the four strong arc exposures obtained in this way that one is selected which is most nearly comparable in general strength with the weak arc spectrum. When the spark spectrum has also been added, it has usually been placed immediately adjoining the weak arc, with the arrangement of the strong arc spectra as before. A few plates have been taken with a Fuess quartz spectrograph, but these have been used exclusively for qualitative purposes.

The arc employed in the work is of the self-feeding type, with carbon poles, working on a direct current (storage battery) circuit of 110 volts. The metal has in all cases been placed in the positive pole.

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[1] Throughout this paper the word "enhanced" is used to denote lines that are strengthened in the spark as compared with the arc.

EXPLANATION OF THE TABLES

The tables which follow contain the results of a study of the elements titanium, vanadium, iron, chromium, and manganese, for a region extending from the ultra-violet to λ 5800. Our investigation of both spot and laboratory spectra is far from complete, but the material here presented seems sufficient for the purpose of a preliminary communication. The tables include all the lines which are affected prominently, and which, through rise or fall in intensity in spot as compared with disk, or in spark or weak arc as compared with strong arc, are especially significant in the present investigation. Until it becomes possible, by the use of improved experimental methods, to increase the magnitude of the effects observed in the laboratory, it is necessary to omit from the discussion such slight apparent changes as are now beyond the limits of accurate observation.

In a discussion of the behavior of the lines of these elements, the investigation naturally divides itself into two parts: the relation of the weak arc to the strong arc, and of the arc to the spark. Accordingly, two sets of tables are given. The first contains the wave-lengths of all the lines which are affected prominently in spots, the amounts by which they are affected, their behavior in the weak arc as compared with the strong arc, and in the spark as compared with the weak arc. For these last two determinations a scale of 0 to 5 has been used, 5 denoting the maximum change. In the column "Identification, Rowland," the absence of an entry indicates that in the Preliminary Table the line is identified with the element considered, a dash that the line is unidentified, while identifications with other lines are given in full. As comparatively few of the fainter lines given in Rowland's table are identified by him, it has been necessary to obtain such identifications for a considerable number of lines, particularly of vanadium and titanium. For the green and yellow region of the spectrum these have been made from measures of plates taken in our laboratory, further results of which will be published at a later time. Excellent tables by Hasselberg of *Ti*, *V*, *Mn*, and *Cr*, and by Rowland and Harrison of *V*, are available, and have been used for the blue and violet region of the spectrum. The

TABLE I

Sun-Spot Lines in Spark and Arc

TITANIUM

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
4060.42		1	2	1		
4112.87		1	2	0–1		
4299.80	*Fe,Ti*	2	3	n.c.		
4300.21		3	2	−2	4	
4300.73		2	3	1		
4338.08		4	3	−2	3	
4351.00		1	0	−2	2	
4387.01	*Ti?*	1	0	−1	3	
4426.20		0Nd?	2	1		
4471.41		0	2	1		
4475.03		0	1–2	n.c.		
4496.32		1	2	0–1		
4501.44	*Ti,* —	5	4	−2	4	
4512.91		3	4–5	1		
4518.20		3	4–5	1		
4522.97		2	4	1		
4533.42		4	5–6	0–1		
4534.95		4	5	1		
4548.94		2	3	0–1		
4555.66		3	4	0–1		
4572.16	*Ti*—	6	5	−2	5	
4617.45		3	4	1		
4623.28		2	3	0–1		
4639.54		2 }	4	1		
.68	*Cr*	0 }				
4639.85		2	3	1		
4640.12		1	3–4	1		
4645.37		0	1–2	n.c.		
4656.64		3	5	1–2		
4682.09		3	5	1–2		
4693.85		0	1–2	0–1		
4722.80		0	2	0–1		
4742.98		1	2	0–1		
4758.31		1	2	1		
4799.98		1	2	0–1		
4820.59		1	3	1		
4841.07		3	4	1–2		
4856.20		1	3	1		
4868.45		0	1–2	0–1		
4870.32		1	2	1		
4885.26		2	3	1		
4900.10	*Ti, La*	2	3	1		
4913.80		2	3	1		
4928.51		0	1–2	1		
4981.91		4	5	1–2		
4991.25		3	4–5	1–2		
4997.28		0	2	1		
4999.69	*Ti, La*	3	4–5	2		

TABLE I—*Continued*

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
5009.83	*Ti, Co*	00	2–3	1–2		
5016.34		2	4	1		
5020.21		2	3–4	1–2		
5023.05		2	3	1		
5025.03		3	4–5	1		
5025.75		1	2	1		
5036.64		2	4	1–2		
5038.58		2	3	1		
5040.14		3	4	1–2		
5064.84		3	4–5	2		
5087.24		0	2	1–2		
5147.65		0	2	1–2		
5173.92		2	3	1–2		
5186.07		2	1	–1	2	
5193.14		2	3	2		
5210.56		3	4–5	2		
5219.88		0	3	1		
5238.74		000N	2	1–2		
5266.14		0	1	1–2		
5282.58		00	1	0–1		
5336.97	*Ti*, —	4	3	–2	3	
5426.47	—	00	3	1–2		H.
5460.72	—	00	3	1		H.
5471.41		000	2	1–2		
5474.44	*Ti?*	00	1	1		
5477.90		00	1–2	1		
5482.08	—	00	1–2	0–1		H.
5490.37		0	3	1–2		
5490.90	—	0 }	2	n.c.		H.
91.04	—	000 }				
5504.12		0	1	1		
5512.74		2	4	2		
5514.56		2	3–4	2		
5514.75		2	3	2		
5523.47		000 }	0	1		
.55		000 }				
5565.70		00	2	1–2		
5644.26	—	00 }	2–3	2		
.37		0 }				
5648.80		00	2	1		
5662.37		0	2–3	1		
5680.15	—	000	0	1		H.
5702.88		000	0–1	1–2		
5716.67		00	2	1–2		
5720.67	*Ti*, A	0	2	1		
5739.70	—	0	1–2	0–1		H.
5740.20	—	0	1	0–1		H.
5766.55		0	1–2	1		
5774.25	*Ti*, A	0	1	1		
5786.19	*Ti, Cr*	0N	2	0–1		
5804.48		0	1–2	1		
5866.68		3	5	2		

TABLE I—*Continued*

CHROMIUM

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
4339.62		4	5	2		
4351.22		3	4	2		
4371.44		2	3–4	1–2		
4373.42		1	3	1		
4540.67		2	3	1		
4555.16	—	2	1	–1	1	L.
4558.83	*Cr ?*	3	2	–1	4	
4571.85		1	1–2	n.c.		
4580.23		3	4–5	1		
4588.38	—	3	2	–1	3	H., L.
4600.93		3	5	2		
4616.30		4	6	2		
4618.97	*Fe*—	4d ?	3		1–2	L.
4626.36		5	7	1–2		
4646.35		5	6	2		
4651.46		4	6	1		
4652.34		5	7	2		
4756.30		2	3–4	1–2		
4789.53		2	3	1–2		
4824.32	*Fe*	3	2	–1	4	L.
4829.55		2	3	1		
4836.42	—	0	00		1	L.
4848.44	—	2	1		3	H., L.
4862.03		0	2	1		
4887.19	*Ni, Cr*	2	2–3	1		
4936.51		1	2	0–1		
4942.66		2	3	1		
5073.11		1	2	1		
5123.64		000	0	1		
5144.85	*Cr, C*	00	1	0–1		
5166.45	*Cr–Fe*	3	4	1		
5227.04	*Fe–Cr*	3	3–4	1		
5230.38	*Co, Cr*	00	0–1	0–1		
5237.49	*Cr ?*	1	0–1		3	
5239.14		00	1	n.c.		
5243.53		00	0–1	0–1		
5247.74		2	3–4	2		
5264.33		4 }	10	2		
.42	*Ca*	3 }				
5275.93		1	1–2	1		
5296.87		3	5	1–2		
5298.46		4	6	2		
5300.93		2	3	1–2		
5335.05	*Co*	1	0		2	
5345.99		5	6–7	2		
5348.51		4	5	1–2		
5410.00		4	6–7	3		
5442.63		00	0–1	n.c.		
5620.72	*Fe*	0	00		2	

TABLE I—*Continued*

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
5694.96		0	1	1		
5702.54		0	0–1	1		
5712.99		0	1	1		
5783.29		2	2–3	0–1		
5784.08		3	4	1		
5785.19		2	3	0–1		
5785.95		1	2–3	n.c.		
5788.14		4	5	1		
VANADIUM						
3910.98	*Fe–V*	4	5	1		
4090.73		1	2	1		
4099.94		2	3	1		
4105.32		2	3	1		
4115.33		3	4	1		
4116.63		1 }	2–3	1–2		
.71	*V, Fe?*	0 }				
4128.25	*Ce–V,–*	6d	7	1		
4232.76		00	1	0–1		
4330.19		0N	2	1–2		
4332.99		0	2	2		
4341.17		0	2	2		
4379.40		4	5	2		
4390.15		2	3	2		
4392.24	*V?*	1N	2	n.c.		
4395.41	*V, Zr*	2	3	1–2		
4400.74		1	2	1		
4406.81	*V–*	2	4	2		
4416.64		0	2	1		
4421.73		0	2	1–2		
4428.71	*V–Cr*	1d?	2	1		
4436.31		0	2	1–2		
4438.01		0	2	2		
4441.88	*V–*	3Nd?	5	2		
4444.57	*V–Ti*	00	2	1–2		
4452.17		0N	2	0–1		
4459.92		1	3	2		
4545.51	*Cr–V*	0	1	1–2		
4577.36		0	2	2		
4580.59		1	2	2		
4586.55		1	2–3	2		
4594.30		2N	4	2–3		
4635.35		00N	1	1		
4831.83		00	2	2		
4832.62		00	2	2		
4851.69	*Ca, V*	1	3	2–3		
4864.92		0	3	3		
4875.67		1	3	3		
4881.74		1N	3	3		

TABLE I—*Continued*

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
5176.95		000	0	n.c.		
5625.10	—	000	0–1	1–2		H.
5626.25	—	000N	1–2	n.c.		H.
5627.86		00	3	2		
5632.67	—	000Nd ?	0	0–1		H.
5646.32	—	000N	1–2	1–2		H.
5657.67	—	000	1–2	1		H.
5668.59		000	2	1		
5671.07		0	3	1–2		
5698.75		1	4	2		
5703.80		1	3	2		
5707.20		0	3	1–2		
.26	*Fe*	1				
5727.27	*Ti–V*	2N	4–5	2		
5727.87	—	00	3	1–2		H.
5731.44	—	00	3–4	1–2		H.
5734.26	A ?	000	1	n.c.		H.
5737.29	—	0	3	1–2		H.
5743.64	—	00	3	2		H.
			IRON			
4258.48		2	3–4			Widening probably due to 58.64 =Hasselberg's *Ti* 58.68
4508.46	*Fe ?*,–	4	3		2	
4522.80	—	3	2	–1	2	L., Re.
4556.06	—	3	2		1	L., Re.
4584.02	*Fe*–	4	3	–1	3	
4603.13		6	7–8	1		
4630.31		4	5	n.c.		
4733.78		4	6	1		
4924.11		5	4	–1	3	
5018.63		4	3	–1	3	
5022.41		3	2	–1		
5110.57		5d	6–7	1		
5169.07		3	5–6	–2	4	
.22		4				
5198.89		3	4	0–1		
5218.37		1	0		2	Enhancement in spark may vary
5225.70		2	3–4			Widening probably due to 25.88=Rowland's *V* 25.92
5250.82		3	4	0–1		
5269.72		8d ?	10	2		
5276.17	*Fe ?*	3	4	n.c.	0–1	
.24	–*Cr ?*	2				
5316.79		4	2–3	–1	2	
5328.24		8d ?	9	1		
5370.17		6	5	–1		
5371.66	*Cr ?*	4	10	2		
.73		3				
5373.90	*Fe, Cr*	2	3	0–1		

TABLE I—*Continued*

λ Rowland	Identification Rowland	Solar Intensity	Spot Intensity	Amount Increase Weak Arc	Amount Enhancement Spark	Remarks
5381.22		2	1			*Ti* line 5381.20 is enhanced 3
5397.34		7d?	8–9	1–2		
5404.36		5	4	–1		
5405.99		6	7	1–2		
5429.91		6d?	7–8	2	0–1	
5447.13		6d?	8–9	2	0–1	
5455.67	*Fe?*	2	7	1		
.83		4				
5497.74		5	7	1		
5501.68		5	6	0–1		
5507.00		5	6–7	1		
5586.99		7	8	0–1		
5712.10		3	6			Hasselberg gives *Ti* at 5712.07
			MANGANESE			
4762.57		5	6	1		
4823.70		5	6–7	1–2		
5255.49		0d?	0–1	n.c.		
5377.80		2N	1	–1	0–1	
5394.84		1	4–5	2		
.91		1				
5407.59		0	2	1		
.69		0				
5420.51		0N	3–4	1–2		
.61		0N				
5432.75		1Nd?	3–4	2		
5470.80		0	3	1		
.88		0				
5506.10		1	1–2	n.c.		
5516.95		0	2	1		
17.03		0				
5537.93		00	2	1		
38.02		00				

abbreviation "H", under "Remarks," in the last column of our tables, indicates that Hasselberg gives a line at this point which we consider to be identical with the solar line in question. Similarly "L" and "Re" refer to the tables of enhanced lines published by Lockyer and Baxandall, and Reese, respectively. The spot intensities of the lines for the region extending from the violet to λ 5000 have been determined from photographs of the spectrum of the large spot of the latter part of June. The remainder are obtained from a combination of results from these plates with those from plates of numerous small spots taken previously.

TABLE II

"Enhanced" Lines in Arc and Spark

TITANIUM

λ Rowland	Identification Rowland	Solar Intensity	Amount Enhancement Spark	Amount Decrease Weak Arc	Remarks
3722.73	*Ti–Fe*	6	2	1	
3757.82	*Cr–Ti*	4	3	2	
3759.45		12d?	5	2	
3761.46		7	5	1–2	
3900.68	*Ti–Fe*	5	5	1	
3913.61	*Ti–*	5d?	5	1	
4012.54	*Ti, Ce*	4	2	0–1	
4028.50	*Ti–Ce*	4	3	1	
4053.98	*Cr–Fe–Ti*	3	3	n.c.	
4161.68	—	4	1–2	0–1	H.
4163.82	*Cr–Ti,–*	4	5	2	
4172.07	*Ti, Fe*	2	5	1	
4290.38		2	3	1	
4294.20		2	2	2	
4300.21		3	4	2	
4302.08		2	1–2	1	
4313.03		3	3	2	
4314.96		1	2	1	
15.14		3			
4316.96	*Ti?*	1	1	1	
4338.08		4	3	2	
4341.53	*Ti?*	2	1	1	
4344.45	*Ti–*	2	2	2	
4351.00		1	2	2	
4367.84		2	4	2	
4387.01	*Ti?*	1	3	1	
4395.20		3	4	1–2	
4399.94	*Ti, Cr*	3	2	2	
4411.24	*Cr–*	1	4	0–1	
4443.98		5	4	2–3	
4468.66	*Ti–*	5	4	2	
4488.49	—	1	3	1	H.
4501.44	*Ti, –*	5	4	2	
4534.14	*Ti–Co*	6	3	2	
4549.81	*Ti–Co*	6d?	5	2	
4563.94		4	4	2	
4572.16	*Ti–*	6	5	2	
4590.13	—	3	2		H.
4805.28	—	3	2	0–1	H.
4911.37	—	1	4		H.
5072.48		0	1		
5129.34	*Ti?*	3	3	1–2	
5154.24	*Ti–Co*	2	1	1	
5186.07		2	2	1	
5188.86		2	5	1	
5226.71	*Ti–*	2	4	2	
5336.97	*Ti,–*	4	3	2	
5381.22	*Fe*	2	1–2	1–2	H.
5418.98	*Ti?*	1	1–2	1	

TABLE II—*Continued*

CHROMIUM

λ Rowland	Identification Rowland	Solar Intensity	Amount Enhancement Spark	Amount Decrease Weak Arc	Remarks
3603.83	—	2	3	1	H.
3678.04	—	2	4	n.c.	H.
3715.32	—	2	3–4	1	
3865.67	*Fe–C*	7	3		H.
3979.66	*Nd–Co*	4	1–2	1	L.
4012.63		0	0–1	1	
4145.91	—	1N	3		L.
4179.41	*Cr, Co*	0	1	n.c.	
4225.02	—	2N	1–2		L.
4242.54	—	2	3		L.
4284.38	—	2Nd?	1	1	L.
4555.16	—	2	1	1	L.
4558.83	*Cr?*	3	4	1	
4588.38	—	3	3	1	H.
4592.23	*Cr–*	1	0–1		
4634.25	—	2	1	1	H.
4824.32	*Fe*	3	4	1	L.
4848.44	—	2	3		L.
4876.59	—	1	2		L.
5237.49	*Cr?*	1	3		
5335.05	*Co*	1	2		
5620.72	*Fe*	0	2		

VANADIUM

λ Rowland	Identification Rowland	Solar Intensity	Amount Enhancement Spark	Amount Decrease Weak Arc	Remarks
3899.28	—	2	4	2	H.
3903.40	*V–Ce?*	2	4	2	
3916.55	—	3	3	2	H.
3952.10	*Mn, V*	2	4	2	
3968.24			2	1	Hasselberg's λ
3973.80	*Nd, V, Fe*	1	3	2	
3997.26	*Cr?*	1	2	1	H.
4003.08	—	2	2	1	H.
4005.86	*V*	3	5	2	
4023.53	*V, Co*	3	4	2	
4035.77			4	2	Hasselberg's λ
4036.92	*V,–*	1	1	1	
4202.51	—	0Nd?	2	1	H.
4205.24	—	1	2–3	1	H.
4225.38	—	0	2	1	H.

IRON

λ Rowland	Identification Rowland	Solar Intensity	Amount Enhancement Spark	Amount Decrease Weak Arc	Remarks
4173.62	—	3	0–1	0–1	L.
4179.02	—	3	0–1	1	L.
4219.52		4	1	0–1	Re.
4233.33	*Mn*	4	1–2		L., Re.
4303.34	—	2	1		L., Re.

TABLE II—*Continued*

λ Rowland	Identification Rowland	Solar Intensity	Amount Enhancement Spark	Amount Decrease Weak Arc	Remarks
4385.55	—	2	1		L., Re.
4433.39		3	0–1	1	
4466.73		5	1	0–1	
4508.46	*Fe ?*,–	4	2		
4515.51	—	3	2	1	L., Re.
4520.40	*Fe ?*,–	3	1	0–1	
4522.80	—	3	2	1	L., Re.
4541.48	—	0	1		L., Re.
4549.64		2	3	1–2	
4556.06	—	3	1		L., Re.
4576.51	—	2	0–1		L., Re.
4584.02	*Fe*—	4	3	1	
4789.85		3	0–1	n.c.	
4924.11		5	3	1	
5018.63		4	3	1	
5169.07		3 }	4	2	
.22		4 }			
5276.17	*Fe ?*	3	0–1	n.c.	
5316.79		4	2	1	
5429.91		6d ?	0–1	–2	
5447.13		6d ?	0–1	–2	

The second series of tables consists of a comparison of the intensities of the lines of these elements which are considerably enhanced in the spark, with their intensities in the weak arc. Most of these lines which occur in the less refrangible part of the spectrum are diminished in spots, and such lines will appear in both sets of tables. As is well known, however, the great majority of strongly enhanced spark lines occur in the violet and ultra-violet, where the spot lines seem to have the same intensity as the Fraunhofer lines. Accordingly, independent lists of these lines have been added, since the evidence afforded by them as to the relation of spark to weak arc is of extreme importance. Almost all of these lines are unidentified in Rowland's table—a result which is of course due to his use of the arc lines for purposes of identification. Consequently, we have been obliged to identify many of them, and in the course of this work have used the tables of Hasselberg and the lists of enhanced lines by Lockyer and Baxandall, and by Reese, to great advantage. References to these lists are made in the same way as in the preceding tables.

We have attempted throughout these tables to include only those cases of blends in which the element under which they are classified in each instance seems to be the predominant factor in producing the effect.

DISCUSSION OF THE TABLES

Before entering upon a discussion of the evidence afforded by these tables, it will be well to indicate to what extent they are to be regarded as comprehensive, and to examine the character of the lines not appearing in them. At the outset the important statement should be made that we have found very few lines which are certainly strengthened or weakened in the low-current arc that are not either spot lines or lines enhanced in the spark. There are, of course, in spot, in weak arc, and in spark many instances near the limits of accuracy of estimates of intensity, but for unquestionable cases the statement above seems to be true. To what extent the converse, that all spot lines are affected in the weak arc, the spark, or both, fails to hold, the tables indicate, and this side of the subject we shall discuss later in this paper.

The lines which are affected in spots and which do not appear in these lists fall into two classes. The first consists of lines so faint that they fail to appear upon our laboratory photographs, or are too weak to furnish quantitative results. The second class consists of lines for which the means of our determinations of change of intensity fall below what we consider the limits of accuracy. In the second class, accordingly, there should be no lines which are prominently affected in our photographs of spot spectra, and we believe this to be the case. The majority of the lines which are too weak upon our photographs to admit of satisfactory discussion belong to iron and chromium. Since any marked cases of strengthening in the low-current arc as compared with the strong arc would be visible for most of these lines, it is clear that such indirect evidence as they afford is in agreement with the fact that the fainter spot lines belonging to these elements are inconspicuous. The evidence furnished by lines enhanced in the spark, for which the absence of an entry in the column "Amount Decrease Weak Arc" indicates that the line is not visible in the weak arc, is considerably more important. Since most of these lines can be seen in the strong arc, it is clear that they are weakened in the low current arc and that only quantitative data are lacking.

In order to simplify the analysis of these tables we shall discuss separately the cases of lines strengthened in spots, and those weakened in spots. An inspection of the results for lines of the first sort gives the following summary:

TABLE III

Element	No. of Lines Strengthened in Spots	No. of Lines Strengthened in Weak Arc	Unchanged Weak Arc
Ti	88	83	5
Cr	46	42	4
Fe	19	18	1
V	56	52	4
Mn	11	9	2
	220	204	16

The relatively small number of *Fe* lines in this summary is due to three causes: first, numerous *Fe* lines are weakened in spots; second, a large number of lines are only very slightly affected, if at all; third, many *Fe* lines are very faint in the arc spectrum, and do not appear on our plates.

The evidence afforded by this comparison of results certainly indicates very strongly the connection of spot lines with those strengthened in the weak arc. The exceptions form but seven per cent. of the total number, and it seems probable that many of these may be accounted for either by misidentification in Rowland's table or by the presence of close companions in the solar spectrum to which the change of intensity in the spot is due. In the table for iron three cases of the latter kind are indicated by notes, and no doubt others exist.

The relation of the lines weakened in spots to those in the spark and the low-current arc is one of the most interesting results of this investigation. The following brief table gives a summary for such lines:

TABLE IV

Element	No. Lines Weakened in Spot	No. These Enhanced in Spark	No. Not Changed in Spark	No. Diminished in Weak Arc	No. Not Seen in Weak Arc	No. Not Changed Weak Arc
Ti	8	8	0	8	0	0
Cr	10	10	0	6	4	0
Fe	13	10	3	9	3	1
Mn	1	1	0	1	0	0
	32	29	3	24	7	1

We have not included in the above list the interesting case of the line λ 5381.22. This line, identified by Rowland as *Fe*, is diminished in spots. No line is given here in the arc tables of Kayser and Runge, nor does it appear upon spark plates of this region. There is, however, a line of *Ti* given by Hasselberg at λ 5381.20 which is enhanced 3 in the spark, and this is probably identical with the solar line.

Further important evidence as to the relation between weak arc, strong arc, and spark is furnished by a number of lines which lie so far to the violet that they apparently are beyond the range of lines affected in sun-spots. This region is particularly rich in lines enhanced in the spark, and it has seemed desirable to consider here also the changes produced in passing from the strong arc to the low-current arc. The following summary derived from Table II includes the most important of these lines. For the sake of completeness the lines comprised in Table IV are also included.

TABLE V

Element	No. Lines Enhanced in Spark	No. These Diminished in Weak Arc	No. Not Seen in Weak Arc	No. Not Changed in Weak Arc	No. Strengthened in Weak Arc
Ti....................	48	44	3	1	0
Fe....................	25	14	7	2	2
Cr....................	22	10	10	2	0
V.....................	15	15	0	0	0
Mn[1]..................	1	1	0	0	0
	111	84	20	5	2

As stated before, we consider the evidence afforded by enhanced lines which fail to appear in the weak arc to be confirmatory of the conclusion that these lines are, in general, diminished in passing from strong to weak arc.

The two lines of iron which appear in the above table as increased in intensity both in spark and in weak arc are the strong yellow lines λ 5429.91 and 5447.13. Both lines are considerably increased in the weak arc, and both are strengthened in sun-spots. We are obliged at present to regard these lines as exceptions. Attention should, however, be called to the fact that both are double in the Sun and probably in the arc as well. This may perhaps account for their contradictory behavior in the spark and the weak arc. The contradiction in the case of spots would, however, still exist, since visual observations in the third order of the 18-foot spectroscope have shown that the amount of strengthening of the two components for each of the lines is about the same, so far as can be judged with the resolving power available.

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[1] Manganese has no prominently enhanced lines in the region which we have investigated. The single line given occurs in the yellow, and it is but slightly affected.

A consideration of the quantitative relations of the enhanced lines of Tables I and II shows that the general agreement between the amount of enhancement in spark and of decrease of intensity in low-current arc is reasonably good, in view of the obvious difficulties in the way of making a comparison on account of the marked difference in the magnitude of the effect in the two cases. The agreement between the amount of decrease in weak arc and in spot is still better, apparently, but too much emphasis should not be laid on this fact, since the range of effect is relatively small. The behavior of silicon, which we have not investigated as yet, should be especially interesting in this respect, its lines being weakened remarkably in sun-spots.

There remains one other feature of this investigation to which attention should be called. This has to do with the negative evidence and serves as a valuable check upon the results obtained. It is evident that in cases in which the intensities of lines in separate spectra are to be compared with each other the best criterion for the correctness of exposure time is given by the lines which are not affected in the two cases. In the present instance we have selected at random from the tables of arc lines for the various elements a series of prominent lines which are not affected in sun-spots. The behavior of these lines in the weak arc and in the flame has then been examined, and the results are indicated in Table VI.

The lines in the "doubtful" column all show some evidences of weakening, but the amounts are at the limit of accuracy of determination and of slight value.

This table affords two kinds of important testimony. The first bears upon the general validity of our hypothesis, which assumes the existence of lines which are affected neither in spots nor in the

TABLE VI

Element	No. of Lines	Strengthened in Weak Arc	Unchanged	Doubtful
Ti..........	37	0	32	5
V...........	39	0	38	1
Fe..........	30	0	26	4
Cr..........	27	0	20	7
Mn..........	19	0	17	2
	152	0	133	19

weak arc. The second goes to show that our quantitative values cannot be affected in any considerable degree by errors in the relative exposure times of our spectra.

In concluding this preliminary discussion of the observational materials, it is well to call attention to one or two essential difficulties in the way of agreement between laboratory and solar results, arising from the nature of sun-spot spectrum photographs. The first of these is that in the sun-spot spectrum the blending of close lines or the superposition of lines of different elements is very liable to hide the true behavior of those under consideration. This is especially true in the blue and violet regions of the spectrum, where the number of lines in the solar spectrum becomes very great. The second difficulty arises from the fact that the number of lines shown to be affected upon a sun-spot photograph depends upon a variety of conditions, in particular the character of the definition at the time, and the size of the sun-spot. Accordingly, until a very large amount of observational material shall have furnished what will actually be a definitive list of sun-spot lines (assuming that the sun-spot spectrum itself does not vary essentially), it will be better to confine comparisons of sun-spot and laboratory results to the more important lines in each case.

TEMPERATURE AS THE PROBABLE CAUSE OF THE OBSERVED PHENOMENA

From the above discussion of the lines in our tables it appears that, in general, (1) the lines which are strengthened in spots are strengthened in the 2-ampere arc; (2) the lines weakened in spots are weakened in the 2-ampere arc; (3) the lines weakened in the 2-ampere arc are "enhanced" in the spark.

Although our work must be carried much farther before final conclusions can be drawn, it nevertheless seems probable that the observed differences of intensity, both in the arc and spark and in sun-spots, may be adequately explained by temperature differences. Accordingly, the simplest way of accounting for the characteristic phenomena of spot spectra seems to be on the hypothesis that the metallic vapors in the spot are cooler than the corresponding vapors in the reversing layer.

However, the production of enhanced lines has been ascribed to such diverse causes that we shall defer judgment as to the arc and spark changes until our experiments can be repeated with an electric furnace. The present discussion is consequently to be regarded as a preliminary one, serving to indicate why we are inclined to ascribe the observed phenomena to the effect of varying temperature.

1. In his paper on the synchronous arc Crew states unequivocally: "Increase of phase in these experiments undoubtedly means increase of temperature."[1] The gradual weakening and finally the complete disappearance of the carbon flutings as the phase was reduced; the decreasing intensity of H and K, and the simultaneous increase of the blue calcium line; the increasing relative intensity of the *Al* pair, as compared with the neighboring H and K lines; and the resemblance of the iron spectrum at zero phase to the flame spectrum: are typical of the phenomena observed by Crew. All of these criteria, and others as important, apply as well to our weak arc plates as to those obtained by Crew with the synchronous arc.[2] From this standpoint, therefore, there is no conflict of testimony: Crew's conclusion as to the comparatively low temperature of the low-phase synchronous arc should apply also to the 2-ampere direct-current arc, at least in so far as it depends on the above criteria.

2. In their investigation on the temperature of the arc, Waidner and Burgess found the temperature of the crater to be reduced 70° when the current was reduced from 30 to 15 amperes. They give no results for smaller currents. In view of the fact that the relative intensities of the lines undergo no material change in passing from

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[1] *Astrophysical Journal*, **22**, 201, 1905.

[2] Although the carbon flutings do not disappear in the 2-ampere arc, they are considerably weakened.

30 to 15 amperes, while the change between 30 and 2 amperes is very pronounced, it is probable that the temperature of the crater is considerably reduced at 2 amperes. As for the arc itself, the great reduction in brightness, demanding exposures of four minutes at 2 amperes as compared with 12 seconds at 30 amperes, is strong evidence in favor of a lower temperature, since we know that the total radiation varies as the fourth or fifth power of the temperature. It should be recognized, however, that the change in brightness may be due in considerable part to the change in the amount of luminous vapor.

3. Since the enhanced lines of the spark appear with lower intensity in the 30-ampere arc, and are still further reduced in passing to the 2-ampere arc, no explanation hitherto advanced to account for these lines appears adequate in the present case, unless it be the explanation based on change of temperature. However, the fact that for the observed lines the changes of intensity with current strength are the reverse of those described by Hartmann in certain other cases, indicates the necessity of caution. For example, Hartmann found the enhanced line *Mg* λ 4481 to be greatly strengthened in the arc, as the current was reduced from 8 to 0.4 amperes. He concluded that "the condition for the development of those molecular vibrations to which the line λ 4481 corresponds were much more favorable in the small arc in spite of its lower, or at least certainly not higher, temperature than in the larger arc."[1] In order to keep the 0.4-ampere arc burning, it was necessary to start it several hundred times during the exposure. Hartmann considers it probable that λ 4481 was produced only at the moment of make or break. Sir William and Lady Huggins also ascribe the production of this line to a sudden discharge,[2] and Crew concludes that in a constant voltage circuit small currents, which heat the electrodes less, will result in a higher voltage between the electrodes, and probably a much quicker break than larger currents. According to him, the essential condition for the appearance of spark lines in arc spectra is a high and rapidly changing E. M. F.[3] It may be mentioned here that our exposures to the weak arc were never commenced until it

[1] *Astrophysical Journal*, **17**, 273, 1903.

[2] *Ibid.*, **17**, 145, 1903.

[3] *Ibid.*, **20**, 281, 1904.

was burning steadily, after the poles had been separated sufficiently to prevent all light except that from the arc proper from entering the short slit.

4. The behavior in stars of the lines affected in sun-spots appears to be consistent with the view that temperature changes alone are sufficient to account for their variation in intensity.[1] In *a Orionis*, which we have other reasons (such as the great strength of the blue calcium line and the presence of titanium oxide flutings) to regard as much cooler than the Sun, lines that are strengthened in sun-spots are still further increased in intensity.[2] In *Arcturus*, which is always assumed to have a temperature between that of *a Orionis* and the Sun, the intensities of the lines agree remarkably with those observed in sun-spots.[3] We hope in a future paper to discuss this subject more fully, especially in its bearing on stellar evolution and the classification of stellar spectra.[1]

5. A bolographic study of spot spectra, on which Mr. Palmer is engaged, indicates that the maximum of intensity is very considerably shifted toward the red, as compared with its position in the spectrum of the photosphere. This result is thus in harmony with the view that the temperature of the vapors in spots is lower than that of the photosphere.

6. The application of our results to chromospheric lines may prove to be of importance, but we are not yet in a position to enter into a full discussion of the subject. In a recent paper[4] Fowler has called attention to the weakening of a number of enhanced lines of iron, titanium, and chromium in spots, these lines having been taken from a list of "long or high-level" chromospheric lines. Our observations of the large spot of June, which was particularly favorable for determinations of this sort, give results in close agree-

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[1] Formerly we were inclined to the view that the presence of spot lines in the spectra of red stars indicated the presence of spots like those on the Sun. Our recent work has led us to the opinion that the comparatively low temperature of these stars offers the simplest explanation of the observations.

[2] Hale and Adams, *Contributions from the Solar Observatory*, No. 8, *Astrophysical Journal*, **23**, 400–405, 1906.

[3] Adams, *Contributions from the Solar Observatory*, No. 12, *Astrophysical Journal*, **24**, 69–77, 1906.

[4] *Monthly Notices*, **66**, 361, 1906.

ment with his for these lines. From the evidence discussed in the present communication, however, we should consider the behavior of these lines to be explained much more simply and satisfactorily on a temperature basis than on any which involves the conclusion that they originate at a higher level in the chromosphere than most other lines of the spectrum. In regard to this question, indeed, we see no occasion to differ from Evershed's conclusion[1] that "there is no evidence of differences in the relative intensities of the lines of an element in the higher or lower regions of the flash layer, and the enhanced lines appear to predominate throughout the entire depth of the radiating stratum."[2]

SUMMARY

1. This paper describes a preliminary study of the more important sun-spot lines in the region above λ 5800, belonging to titanium, chromium, iron, vanadium, and manganese—the metals most characteristic of sun-spots.

2. Over ninety per cent. of the lines in our tables, which are strengthened in sun-spots, are found to be strengthened in passing from a 30-ampere arc to a 2-ampere arc.

3. Over ninety per cent. of the lines shown by our plates to be weakened in sun-spots are weakened or absent in the 2-ampere arc.

4. Over ninety per cent. of all the "enhanced" lines included in our tables are weakened or absent in the 2-ampere arc.

5. In a list selected at random of 152 lines which are not spot lines, no cases were found of lines strengthened in the low-current arc or in the flame.

6. We are not yet ready to express a final opinion, but are inclined to the view that temperature differences are adequate to account for the above phenomena. Our reasons for this view may be summarized as follows:

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[1] "Solar Eclipse of 1900, May 28," *Philosophical Transactions*, Series A, **201**, 477.

[2] Bright lines, due to overhanging flocculi or to eruptive phenomena, frequently appear in spot spectra. Indeed, H_3 and K_3 are always present. The weakening of the enhanced lines in spots, however, should in our opinion be classed with the strengthening of other lines, and attributed to the same cause.

a) The similarity of the spectroscopic phenomena of the weak arc to those of the low-phase synchronous arc, held by Crew to correspond to a low temperature.

b) The probable decrease in the temperature of the arc with decreasing current strength.

c) The behavior of the enhanced lines in the 2-ampere arc.

d) The presence of sun-spot lines in red stars.

ADDENDUM

When the above paper was written, it was not supposed that the competence of temperature differences alone to account for the observed phenomena could be tested at present. It was subsequently decided, however, to construct an electric furnace for immediate use in our Pasadena laboratory, where sufficient current is available. A Littrow spectrograph was also built for observations with the furnace. This is supplied with a combined collimating and camera objective, by Zeiss, of 6 inches (15 cm) aperture and 18 feet (5.49 m) focal length, and a Rowland plane grating, with ruled surface 5×3.75 inches (12.7×9.5 cm), having 15,000 lines to the inch (5,900 to the cm), for the use of which we are indebted to the kindness of Professor Ames.

In addition to our work with the furnace, which leaves little doubt that the spot phenomena can be accounted for as effects of temperature, we have obtained independent evidence, by observations of the outer portions of the flame of an ordinary arc, which leads to the same conclusion. In this investigation the metal under consideration, in the form of a powder, was placed in the positive pole. The vapor in the long flame which rises from such an arc is undoubtedly of lower temperature than that between the poles. Photographs of the spectrum of the flame show the bands of the oxide, and give other evidences of low temperature, such as the strengthening of the blue calcium line, which is more intense than H and K. The spectrum of the flame, compared with that of the core of the arc (between the poles), shows changes of line intensity similar to those observed with the 2-ampere arc and the synchronous arc.

In order to test fully the important question of the identity of these variations, we have made an extensive series of comparisons of the weak arc and flame. An independent set of estimates for the lines affected in the flame was first made, and this was then compared with the determinations for the lines affected in the weak arc. The results of this comparison are indicated by the following summary:

TABLE VII

Element	No. Lines Compared	Affected in Same Direction	Affected Same Amount	Amount Greatest Difference
Ti..........	122	111	98	0.5
V..........	49	42	34	0.5
Cr..........	62	57	51	1.0
Fe..........	28	24	20	0.5
Mn..........	12	12	10	0.5

The quantities in the last column are in terms of units of the scale, extending from 0 to 5, used in the estimates of differences of intensity in our previous tables.

It is evident from this comparison that there can be little doubt as to the identity of the effects found to exist in the low-current arc and in the outer portions of the flame of the strong arc. In consequence we may say, in general, that a large majority of the lines that are strengthened in sun-spots are relatively strengthened in the flame, while a similar proportion of those that are weakened in sun-spots are relatively weakened in the flame.

The second part of the evidence is furnished by some results obtained with the electric furnace. This work was undertaken in the hope of observing such variations of intensity as were found in the weak arc, under conditions which would eliminate all possible electrical effects and leave temperature as the only possible agent for producing them.

The furnace used was of a type employed by Moissan. A carbon tube of 1¼ inches (3.2 cm) external and ¾ inch (1.9 cm) internal diameter was passed through the walls of a small rectangular box of retort carbon, imbedded in a large mass of powdered magnesite. At right angles to this tube were placed the carbon poles of a powerful arc, the center of the opening between the poles coming just above the carbon tube. Accordingly, when the current was passed between the poles, the arc played on and over the tube, and the intensely heated chamber assisted in distributing the heat over a considerable portion of its length. A current of about 600 amperes at a potential of 50 volts has been used, and with a few modifications we expect to be able to employ a similar amount of current at 100 volts. The element to be investigated is placed in the interior of the carbon tube, and the light from the opening is projected by a lens upon the slit of the Littrow spectrograph.

With this instrument we have photographed the spectra of iron and manganese, and expect soon to obtain that of chromium as well. It is not yet certain whether it will be possible with this form of apparatus to vaporize the highly refractory elements titanium and vanadium, but we hope to be able to do so with the aid of the higher potential.

A comparison of the plates of manganese and iron in the green and yellow regions with those obtained in the flame and in the low-current arc has proved of the greatest interest and importance. An independent estimation of the relative intensities of the manganese lines upon the furnace plates showed that all ten of the lines of wave-length greater than 5255 given in Table I are affected. Of these seven are affected in the same direction and by the same amount. The enhanced line λ 5377.8 is reduced 2 in the furnace as against 1 in the weak arc; and the lines most strongly affected in the weak arc, λ 5395 and λ 5433, are so greatly strengthened in the furnace as to be reversed. The results given by the iron plate are similar. Of the twenty-four lines to the red of λ 5110 three are too faint upon the furnace plate to be visible. The remaining twenty-one lines are affected similarly in furnace and weak arc, and seventeen of these by the same amount. The largest difference among the other four amounted to but one-half of one division.

OBJECTIONS TO THE TEMPERATURE HYPOTHESIS

A summary of the principal objections to the hypothesis that difference of temperature is the essential factor in producing the phenomena observed by us in flame, spark, and sun-spots will form a desirable corollary to the summary which concluded our main discussion. It will also be of material interest as indicating the directions along which we expect to continue most of our investigations.

The more important of these objections are as follows:

1. The comparative absence in sun-spots of strengthened and weakened lines in the blue and violet portions of the spectrum. While it is true that the differences in the relative intensities of lines in the weak arc and in the strong arc become as a rule less in the more refrangible parts of the spectrum, there are still some marked cases of strengthening in the weak arc of lines which are not affected in sun-spots. Perhaps the most important instances of this sort are the three *Cr* lines λ 4290, λ 4275, and λ 4255. All of these lines are decidedly strengthened in the weak arc and the flame, but are not affected in spots.

To the same category of lines belongs the blue line of *Ca* at λ 4227. This increases in intensity with a diminution of temperature. It does not, however, seem to be affected in spots.

In the case of enhanced lines the matter is still more striking. As is well known, the strongest enhanced lines of nearly all of the elements are found in the ultra-violet. As against this is the fact that the most refrangible line which we have yet observed upon our photographs as unquestionably affected in sun-spots is λ 3906.

Though we have at present no sufficient explanation for this condition of affairs, there are one or two considerations which seem to bear upon it. One of these is the striking similarity in this respect of a photograph of an abnormal solar spectrum obtained in 1894 at the Kenwood Observatory.[1] On this plate the character of the solar spectrum from λ 4100 to λ 3900 is totally changed. Beyond λ 3900, however, the spectrum gradually returns to the normal solar type. While the analogous behavior of sun-spot spectra may be no more than a coincidence, the similarity calls for remark. Furthermore, in view of the fact that certain elements, such as vanadium, manganese, and, in general, titanium, show very close agreement with our hypothesis, while others show important exceptions, the possibility is suggested that the various elements are differently distributed in spots, and that the vapors are not all of the same temperature.

A tentative explanation of the above difficulty might be founded on the hypothesis that the vapors producing the greater part of the characteristic changes in sun-spot lines occur at the base of the reversing layer, where they may form a comparatively thin stratum. Consequently, in the more refrangible part of the spectrum, the absorption of the overlying vapors may be so great as to mask almost completely the selective absorption of this low layer. From this point of view the spectrum of a spot in the more refrangible region would be due mainly to the higher vapors, and would show few differences from the ordinary solar spectrum. The very great falling off in the intensity of the spectrum of the spot as compared with disk in the violet region, where the intensity is only about one-third to one-fifth as great as in the yellow and green regions, probably indicates the action of powerful general absorption. On the above hypothesis this absorption is assumed to be sufficient practically to obliterate the effects of selective absorption, the vapors producing the latter being assumed to be restricted in depth.

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[1] *Astrophysical Journal*, **16**, 211–233, 1902.

2. Some lines in the less refrangible region of the spectrum seem to be strengthened in the spark at the same time that they are strengthened in the flame and in spots. The principal cases of this sort are the iron lines λ 5430 and λ 5447.

3. The changes in the relative intensities of lines in the flame do not in all cases harmonize in amount with those observed in spots. Examples of this sort are evident from an inspection of the tables. Examination of these tables also furnishes some indication of a greater amount of strengthening in the low-current arc of the strong lines than of the weak lines. The evidence is by no means to be considered conclusive, since the exceptions are numerous and important. That the effect, however, is not due to photographic or physiological causes is shown by its persistence upon plates taken with widely varying exposure times. If genuine, it is identical with that claimed by Fowler to exist in the case of spot lines, namely, that such lines are in general affected in spots in proportion to their absolute intensities.[1] This conclusion we had occasion in a former communication to oppose,[2] and it certainly is not borne out by the results for at least two of the elements most prominent in sun-spots, titanium and vanadium. The question of the existence of such an effect for lines

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[1] *Monthly Notices*, 65, 205–218, 1905.

[2] *Astrophysical Journal*, 23, 11–44, 1906.

strengthened in the low-current arc and in the flame we shall hope to settle definitely at an early period in our future investigations.

In this connection, however, it is well to call attention to the fact that in the laboratory work and in sun-spots we are dealing with what are probably considerably different absolute temperatures. Consequently, the different increment of change at different absolute temperatures may well account for some of the discrepancies mentioned above. If it were possible to determine by laboratory experiments the temperature of the spot vapors, further work along this line would be much simplified. Assuming the correctness of our hypothesis, such a method of determining this temperature, though perhaps subject to serious practical difficulties, would be by establishing the equality in the laboratory of a pair of sun-spot lines, one of them an enhanced line, which have been observed as of equal intensity. Since enhanced lines diminish in intensity as the temperature falls, while the other lines increase, equality of intensity in the laboratory should serve to determine the temperature in question.

4. As it seems to be the opinion of several observers that enhanced lines may be produced, at low temperatures, by suitable electrical means, this phase of the subject will require further investigation. Our hypothesis does not maintain, however, that temperature differences offer the *only* means of explaining the observed changes in metallic spectra. It merely assumes that variations of temperature afford a simple and satisfactory way of accounting for the changes in the relative intensities of the spot lines, as observed in the laboratory, in sun-spots, and in stars.

5. The hydrogen lines, as far as $H\delta$, are weakened in our photographs of spot spectra. This fact, taken in conjunction with the great strength of the hydrogen lines in the chromosphere and in the first-type stars (where the enhanced lines are strengthened), and their weakness in red stars, might be made the basis of an hypothesis to account for the weakening of the enhanced lines in red stars and in spots. For Hartmann has shown that the enhanced lines are strengthened in an arc in water, because, in his opinion, of the hydrogen produced by its decomposition. A similar effect of hydrogen atmosphere has been observed by Crew with a rotating arc, but he ascribes the production of the spark lines to a more rapid break, caused by

the presence of the hydrogen, which introduces an extra electromotive force.[1] We have observed the spectrum of a 110-volt continuous-current arc in hydrogen between fixed metallic poles. As there was no break, Crew's explanation does not seem adequate to account for the apparent strengthening of the enhanced lines on our photographs. If the results of this preliminary experiment are confirmed by later work, the hydrogen hypothesis may require further investigation.

It may be recalled that in his paper on "The Evolution of Solar Stars"[2] Schuster suggests the possibility that the extensive hydrogen atmospheres of first-type stars might account for their high temperatures, if it could be shown that hydrogen, perhaps in some form with which we are unfamiliar in the laboratory, absorbs strongly in the infra-red. We are unaware of any evidence pointing to the existence of such absorption, and therefore do not feel at all certain that the high temperatures of first-type stars depend upon their extensive hydrogen atmospheres. Whether the presence of hydrogen can produce an increase in the temperature of arc or spark may perhaps be determined by laboratory experiments now in progress.

AUGUST 1906

NOTED ADDED OCTOBER 2

In revising this paper for publication as a *Contribution from the Solar Observatory*, we are able to include an observation that seems to leave no doubt as to the comparatively low temperature of sun-spots. A careful study of the titanium oxide flutings in the flame of the arc, and a comparison of these flutings with two of our best spot spectrum photographs, clearly demonstrate the presence of at least one of the flutings in the spot. The wave-lengths in the arc of the first two maxima of this fluting we find to be λ 5597.99 and λ 5629.52. In the spot the fluting is represented by a great number of fine lines, with well defined maxima at λ 5597.98 and λ 5629.52. The strong green fluting, beginning about λ 5168, which is so conspicuous a feature of the spectra of third-type stars, may also be represented in the spot, though this is not yet certain.

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[1] *Astrophysical Journal*, **20**, 280, 1904.

[2] *Ibid.*, **17**, 165–200, 1903.

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SUN-SPOT LINES IN THE SPECTRUM OF *ARCTURUS*

By WALTER S. ADAMS

The spectrum of *Arcturus* has always been of considerable interest to those investigating the subject of stellar classification, because of its intimate relationship to that of the Sun. Certain differences have, indeed, been recognized,[1] but since the study of its spectrum, as in the case of most other stars, has been confined almost wholly to a limited region in the blue portion photographed for the purpose of determinations of radial velocity, it has not been possible to establish any very definite relationship with other stars or with the Sun.

In connection with some investigations at this Observatory of the lines affected in sun-spots, a number of photographs in the blue and violet regions of the large sun-spot of the latter part of June were obtained, and a study of these showed the existence of a considerable number of spot lines, some of which occur as far to the violet as λ 3900. The possibility of applying these results to stellar spectra, and particularly to the case of *Arcturus*, at once suggested itself, and the comparison has proved of exceptional interest.

The material available for the study of the star was a plate obtained in July 1905 by Professor Hale and the writer in the course of some investigations on the practicability of using diffraction gratings for the photography of stellar spectra. This plate was taken in the first order of a 5-inch (12.7 cm) Rowland plane grating used in conjunction with two lenses of 5 inches aperture and 149 inches (3.78 m) focal length. The grating was set so that λ 4500 fell at about the center of the plate, and the plate itself was bent to a slight curve. At the time at which this photograph was taken the mirrors of the Snow telescope were considerably tarnished, and the exposure time was very long, amounting to about 23 hours, extended over portions of five nights. An accurate temperature control, however, resulted in a very satisfactory plate, giving an extent of spectrum

[2] V. M. Slipher, "Observations of Standard Velocity Stars," *Astrophysical Journal*, **22**, 323, 1905.

of suitable strength and in good definition from λ 4350 to λ 4900. The linear scale of this plate is 1 mm=4.3 t.-m., which is about two and one-half times as great as that of the more powerful spectrographs used for determinations of radial velocity. The comparison spectrum employed was that of the Sun, three exposures on three of the intervening days having been made in all. This has proved of the greatest value in the study of the plate, since it has been possible to identify practically all of the stellar lines directly without the necessity of measurement, and at the same time the identical solar lines are available for comparison which were used in the estimation of the intensities of the sun-spot lines.

In the tables which follow, the comparison of the spectrum of *Arcturus* with that of spots for the region λ 4350 to λ 4900 is given in full. In view of the importance of sun-spot lines in stellar spectra, it has seemed best to publish a list of these lines for the violet region as well. The study of more sun-spot plates will, no doubt, result in the addition of other lines to this list, as well as in some modifications of the lines given. The intensities are in all cases referred to the intensities for the solar lines given in Rowland's table. The lower photographic resolution on the stellar plate has involved the combination of lines many of which are resolved on the spot plates, and in such cases the intensities of the lines combining to form the blends are given in full in the list of spot intensities. The abbreviation "n. c." indicates that the line is not affected.

The agreement of the results for spot and star in these tables is certainly very striking. Not only are the lines affected in spots similarly affected in the star, but the absolute intensities of the lines are remarkably close in the two cases. The conclusion seems to be unavoidable that the physical conditions existing in sun-spots and in the atmosphere of this star are nearly identical. Should it prove, as seems at present very probable, that the differences between the spectrum of the Sun and that of spots are to be accounted for on the basis of a lower temperaturc in the latter, we must also infer a lower temperature for *Arcturus* than for the Sun.

A study similar to this on the spectrum of *a Orionis*[1] has shown

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[1] Hale and Adams, "Sun-spot Lines in the Spectra of Red Stars," *Astrophysical Journal*, **23**, 400, 1906.

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
3905.66	*Si*	12	10		
3910.98	*Fe–V*	4	5		
3913.61	*Ti*	5	4–5		
3921.56	*Ti*	1	2		
3924.67	*Ti*	4	5		
3930.02	*Ti*	2	3		
3964.32	. .	1	4		
.42	*Ti*	2			
3982.63	*Ti*	2	7		
.74	*Y*	3			
3984.48	*Cr*	2	3		
3991.83	. .	2	3		
3996.68	*Sc*	00	0		
3998.79	*Ti*	4	5		
4053.98	*Cr–Fe–Ti*	3	2–3		
4060.42	*Ti*	1	2		
4082.59	*Sc–Fe–Ti*	3	4		
4090.73	*V*	1	2		
4092.82	*V, Ca*	3 d?	4		
4095.09	*Ca ?*	4	5		
4099.94	*V*	2	3–4		
4105.32	*V*	2	3–4		
4112.87	*Ti*	1	2–3		
4113.07	. .	1	3–4		
.12	*Fe*	3			
4115.33	*V*	3	4		
4116.63	*V*	1	0		
.71	*V, Fe?*	0			
4123.54	*Cr*	0	3–4		
.66	*Ce, V–Mn*	1			
.71	*Ti*	000			
4147.84	*Fe*	4	5–6		
4159.35	. .	5	4–5		
4186.28	*Ti*	1	2		
4190.87	*C, Co*	1Nd?	2		
4200.15	*Fe*	2	3–4		
.26	*Cr*	00			
4209.98	*V*	1	2		
4216.35	*Fe*	3 d?	4		
4232.76	*V*	00	3		
.89	*Fe*	2			
4252.39	. .	00	1–2		
.47	*Co*	0			
4258.48	*Fe*	2	3–4		
4283.17	*Ca*	4	5		
4295.91	*Cr, Ti*	2	3		
4299.15	*Ca*	3	4		
4299.80	*Fe, Ti*	2	3		
4300.21	*Ti*	3	2–3		
4300.73	*Ti*	2	2–3		
4302.69	*Ca*	4	5–6		
4330.19	*V*	0 N	2		
4332.99	*V*	0	1–2		
33.08	. .	0			
4337.72	*Cr*	3	4		

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
4338.08	*Ti*	4	3		
4338.43	*Fe*	1	1–2		
4339.62	*Cr*	4	5		
4340.63	*H*	20 N	15		Weakened on red edge mainly
4341.17	*V*	0	2		
4347.40	*Fe*	1	2		
4351.00	*Ti*	1	0		
4351.22	*Cr*	3	4		
4352.91	*Fe*	4	6–7	7–8	Widened to red
53.04	*V*	0			
4355.26	*Ca* ?	2	2–3	3	
4356.06	. .	0	2	2	
.16	*Ni*	0			
4363.63	. .	0	1–2	2	
.77	. .	0			
4367.75	*Fe*	5	6	n.c.	
.84	*Ti*	2			
4371.14	*Zr*	1	n.c.	6	
.22	. .	1	n.c.		
.32	. .	00	n.c.		
.44	*Cr*	2	3–4		
4372.50	. .	0 d ?	1	1	
4373.42	*Cr*	1	2	2	
4382.85	*Mn*	0	1	. .	In star this line is covered by shading of λ 4383.72
.93	–*Fe*	2			
4387.01	*Ti* ?	1	0	. .	
4390.15	*V*	2	3–4	3–4	
4391.82	*Co*	0		5	
91.92	*Cr*	1	3		
92.03	*Co*	0			
92.24	*V* ?	1 N	2		
4393.20	*V* ?	0	1	0–1	
4395.20	*Ti*	3	3–4	7	
.41	*V*, *Zr*	2	3		
4400.74	*V*	1	2–3	3	
4406.81	*V*–	2	4	5	
4407.81	*V*	2	7–8	7	
.87	*Fe*	4			
4408.36	*V*	2	3	3	
4408.58	*Fe*	3	6	6	
.68	*V*	2			
4412.30	*V*	00	2–3	4	
.42	*Cr*	0			
4416.64	*V*	0	2–3	3	
4416.98	. .	2	1–2	1	
4417.45	*Ti*	0	2	3	
.58	*Co*	00			
4419.94	*Mn*	00 N	1	1	
20.10	*V*	00 N			
4421.73	*V*	0	2	2	
4423.30	*Fe*	1	2	2–3	
.43	*Cr*	0 N			
4426.20	*Ti*	0 Nd ?	2	2	
4427.27	*Ti*	2	3	8	
.48	*Fe*	5	n.c.		

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
4428.71	*V–Cr*	1 d?	2	2	
4429.96	*V*	00	1	1–2	
4433.95	*Fe*	1	n.c.	2	
34.17	*Ti*	0Nd?	1		
4435.13	*Ca*	5	6	8	
.32	*Fe*	2	n.c.		
4436.31	*V*	0	2	3–4	
.52	*Mn*	2	n.c.		
4437.73	..	0	n.c.	4	
37.86	..	00	n.c.		
38.01	*V*	0	2		
4441.88	*V–*	3Nd?	5	4–5	
4443.98	*Ti*	5	4–5	4–5	
4444.57	*V–Ti*	00	2	4	
.73	*Fe, Ti*	2	n.c.		
4445.64	*Fe*	1	2–3	2–3	
4449.31	*Ti*	2	2–3	n.c.	
4452.17	*V*	0 N	2	2	
4453.88	*Ti*	1	1–2	1–2	
4455.98	*Mn*	2	6–7	6	
56.06	*Ca*	3			
4456.79	*Ca*	2	3–4	3	
4459.92	*V*	1	3	3	
4460.39	*V*	0	4	4	
.46	*Mn*	1			
.52	..	0			
4462.16	*Fe–Mn*	3Nd?	3–4	4	
4465.98	*Ti*	1	2	1–2	
4468.66	*Ti–*	5	4–5	n.c.	
4469.87	*V*	00	0	..	Blended in star with lines to violet
4471.41	*Ti*	0	2	1–2	
4471.72	..	00 N	1–2	2–3	
.85	..	0			
.97	..	00			
4475.03	*Ti*	0	1–2	2	
4488.49	..	1	0–1	n.c.	Enhanced line of *Ti*
4496.12	..	1	n.c.	4	
.32	*Ti*	1	2		
4497.84	*Ti*	0 N	1–2	1	
4501.44	*Ti*, –	5	4	4–5	
4503.93	..	00	1	n.c.	
04.04	*Mn*	00			
4508.46	*Fe?*, –	4	3	2–3	
4512.91	*Ti*	3	4–5	4	
4518.20	*Ti*	3	4–5	4	
4518.75	..	0	2	2–3	
.87	*Ti*	0			
4522.69	*Fe?*	0	n.c.	7	
.80	..	3	2		4522.80 is an enhanced line of *Fe*
.97	*Ti*	2	4		
4527.49	*Ti*	3	5	5	
.63	..	0			
4533.42	*Ti*	4	5	5	
4534.95	*Ti*	4	5	5	

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
4535.74	*Ti*	3	5–6	6	
.88	*Cr*	1			
.91	*Zr*	0			
4536.09	*Ti*	2	5–6	6	
.22	*Ti*	2			
4540.67	*Cr*	2	3	n.c.	
4544.79	*Cr*	1	5	5	
.86	*Ti*	3			
4545.51	*Cr–V*	0	1	1	
4546.13	*Cr*	3	4	4	
4548.94	*Ti*	2	3	3–4	
4549.64	*Fe*	2	7	6	
.81	*Ti–Co*	6d ?			
4552.63	*Ti*	2	4–5	4	
.72	*Fe*	1			
4555.66	*Ti*	3	4–5	4	
4556.06	. .	3	2	5	
.31	*Fe–Cr*	4	n.c.		
4558.83	*Cr ?*	3	2	1	Enhanced line of *Cr*
4560.10	*Ni, Ti*	0	1	2	
4562.81	*Ti*	00	1–2	2	
4563.94	*Ti*	4	3–4	3	
4569.69	*Cr*	00	1–2	1–2	
.79	*Cr*	0			
4571.28	*Mg*	5	6	7	
4571.85	*Cr*	1	1–2	1–2	
4572.16	*Ti–*	6	5	4–5	
4574.90	*Fe*	2	3	3–4	Widened to red
75.08	. .	00 Nd ?			
4575.73	*Zr*	00 N	0–1	1	
4576.51	. .	2	1	1	
4577.36	*V*	0	2–3	3	
4578.73	*Ca*	3	5	5	
.91	*V*	00 N			
4580.23	*Cr*	3	4–5	4–5	
4580.59	*V*	1	2–3	3	
4581.58	*Ca*	4	10	10	
.69	*Co, Fe*	4			
4584.02	*Fe–*	4	3	3	Enhanced line of *Fe*
4586.05	*Ca*	4	6	5–6	
.16	. .	0			
4586.55	*V*	1	3	3–4	
4588.38	. .	3	2	1	Enhanced line of *Cr*
4594.30	*V*	2 N	4–5	4	
4600.93	*Cr*	3	5	6	
01.11	. .	0	n.c.		
01.21	*Cr*	0	0–1		
4603.13	*Fe*	6	7–8	7	
4606.40	*Ni, C*	2	3	2–3	
4607.51	*Sr*	1	2–3	2	
4616.30	*Cr*	4	6	5	
4617.45	*Ti*	3	4–5	4	
4619.71	*Cr*	1	1–2	3–4	
.96	. .	00	1–2		
4620.69	*Fe*	1	0	0	

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
4622.06	*Cr*	0	3	3	
.13	*Cr*	1			
4623.28	*Ti*	2	3	3	
4626.36	*Cr*	5	7	6	
4630.31	*Fe*	4	5	5	
4635.35	*V*	00 N	1–2	1–2	
4639.54	*Ti*	2	4	4–5	
.68	*Cr*	0			
4639.85	*Ti*	2	3–4	7	
40.12	*Ti*	1	3–4		
4645.37	*Ti*	0	2	2–3	
4646.35	*Cr*	5	6	6	
4650.19	*Ti*	0	1	1–2	
4651.46	*Cr*	4	6	5	
4652.34	*Cr*	5	7	7	
4653.55	. .	00	1–2	1	
.68	. .	00			
4656.23	*Ti*	0	1–2	1–2	
.36	*Cr*	0			
4656.64	*Ti*	3	5	5	
4657.38	*Ti?*	2	1	1	
4664.96	*Cr*	3	4	n.c.	
4668.75	. .	1 N	2–3	2	
4670.59	. .	2	3	4	
4675.29	*Ti*	1 N	2	2	
4680.48	. .	1	2	2	
4682.09	*Ti*	3	5	5	
4685.45	*Ca*	2 N	3	3	
4687.85	. .	00	1–2	2	
.98	*Zr*	0			
5688.36	*Fe*	2	1	2–3	
.55	. .	0	1		
4690.98	*Ti*	00	0–1	1	
4693.85	*Ti*	0	1–2	2	
4698.58	*Co*	0	n.c.	5	
.64	*Cr*	1	n.c.		
.80	*Cr*	1	n.c.		
.95	*Ti*	1	2		
4710.37	*Ti*	00	5	5	
.47	*Fe*	3			
4715.47	*C?*	00	2	2–3	
4717.76	. .	0	1	2	
4718.60	*Cr*	3	4	n.c.	
4722.80	*Ti*	0	2	2–3	
4723.29	*Cr*	00	3	4	
.36	*Ti*	00			
4729.86	*Fe? Cr*	1	1–2	1–2	
4733.78	*Fe*	4	6	6	
4742.98	*Ti*	1	2	2	
4744.01	. .	000	1	. .	
4744.57	*Fe?*	3	2	2	
4748.32	*Fe?*	4	3	2	
4752.01	*Na?*	00	0–1	0	
4755.34	. .	00	0	. .	
4756.30	*Cr*	2	3–4	3	

λ	Element	Intensity in Sun	Intensity in Spot	Int'nsity in Star	Notes
4758.31	*Ti*	1	2	2	
4762.57	*Mn*	5	6	7	
4771.28	*Ti–Co*	00	1	2	
4778.44	*Ti*	00	0–1	0	
4779.63	*Fe*	1	2	2	
4781.91	. .	00	1–2	2–3	
4789.53	*Cr*	2	3	3	
4792.70	*Ti–Cr*	2	3	3–4	
4799.98	*Ti*	1	2	2	
4805.61	*Ti*	0	1	2	
4807.18	*Ni*	2	1–2	1–2	
4820.59	*Ti*	1	3	3	
4821.31	. .	0	000	00	
4823.70	*Mn*	5	6–7	6	
4825.53	. .	00	1	1	
.67	*Ti*	000			
4827.64	*V*	000	2	2–3	
.80	*Ti*	00			
4829.55	*Cr*	2	3	3	
4831.36	*Ni*	3	2–3	2	
4831.83	*V*	00	2–3	3	
4832.62	*V*	00	2	3	
4832.90	*Fe*	3	2	2	
4836.42	. .	0	00	00	
4841.07	*Ti*	3	4–5	4	
4847.50	*Ca*	0	2	1–2	
4848.44	. .	2	n.c.	3	
.60	*Ti*	0000	0–1		
4849.08	*Fe*	1	1–2	1–2	
4851.69	*Ca, V*	1	3–4	4–5	
4856.20	*Ti*	1	3	3	
4861.53	*H*	30	25	25	
4862.03	*Cr*	0	2	. .	In star this line is lost in shade of $H\beta$
4864.92	*V*	0	3	3	
4868.45	*Ti*	0	1–2	3	
.60	. .	00 d?	n.c.		
4870.32	*Ti*	1	2	2	
4875.67	*V*	1	3	3	
4876.59	. .	1	0	0	
4881.74	*V*	1 N	3	5	
.90	*Fe*	2	n.c.		
4885.26	*Ti*	2	3–4	3	
4885.96	*Cr*	0	1–2	n.c.	
86.13	*Cr*	00			
4888.71	*Cr*	00	4	3–4	
.82	*Fe*	2			
4893.03	*Fe*	1	0–1	0	
4900.10	*Ti, La*	2	3–4	4	

that sun-spot lines are also present in the spectrum of that star. The amount by which they are affected, however, is, as a rule, considerably greater than in the case of spots or of *Arcturus*. We have, accordingly, in Sun, *Arcturus*, and *a Orionis*, a series arranged in the order of increasing differences for the characteristic spot lines. In the event referred to above—namely, that these differences can be accounted for on a temperature basis—this sequence would represent a scale of descending temperatures.

In a recent letter to Professor Hale, received while this investigation was in progress, Mr. Baxandall, of the Solar Physics Observatory at South Kensington, refers to some studies of the spectrum of *Arcturus* made by himself in the blue region of the spectrum. The absence of a list of sun-spot lines in this region prevented him from making a direct comparison, but his conclusion, that most of the titanium and vanadium lines in the spectrum of *Arcturus* are considerably stronger than in the Sun, is in agreement with the results found in this discussion.

I am indebted to Messrs. Gale and Ellerman for the sun-spot plates used in this investigation.

Solar Observatory,
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A 100-INCH MIRROR FOR THE SOLAR OBSERVATORY

By GEORGE E. HALE

I am permitted to announce that Mr. John D. Hooker, of Los Angeles, has presented to the Carnegie Institution of Washington the sum of forty-five thousand dollars, to be used to purchase for the Solar Observatory a glass disk 100 inches (2.54 m) in diameter and 13 inches (33 cm) thick, and to meet other expenses incident to the construction of a 100-inch mirror for a reflecting telescope of 50 feet (15.24 m) focal length. These expenses will include the erection of a building in which the mirror can be ground, figured, and tested; the construction of a large grinding-machine, with crane for lifting the mirror; the provision of a 54-inch (1.37 m) glass disk, to be made into a plane mirror for testing purposes; the purchase of glass disks for the various plane and convex mirrors required in the telescope, etc. The optical work will be done by Professor G. W. Ritchey and the assistant opticians employed under his direction by the Solar Observatory.

In making this gift, Mr. Hooker's desire is to secure the realization of the great possibilities in astrophysical research which a large reflector seems to offer. He has absolute confidence in the ability of Professor Ritchey to make an essentially perfect mirror 100 inches in diameter; no one could ask better evidence of this than his gift affords. He knows, also, that in several classes of work, such as the measurement of the heat radiation of the stars, and the spectroscopic study of the faintest objects, the mirror is sure to yield results fully commensurate with its great size. But he is nevertheless aware that for certain other classes of work, in which the most perfect definition is essential to the highest success, the construction of a mirror of such great aperture must be regarded as an experiment. The immense block of glass will weigh four and one-half tons—four and a half times as much as the disk of our 60-inch (1.52 m) mirror. The difficulty of providing a mounting capable of carrying it with the necessary precision is not slight. The glass is certain to be distorted by temperature changes, which would ruin its performance if not obviated. The atmospheric conditions, even on Mount Wilson, may not be sufficiently good to permit so great an aperture to be used to full advantage. Of these and other obstacles Mr. Hooker is fully informed, and he does not underestimate their importance. But he perceives and appreciates, with the understanding of one who has himself invented and developed mechanical appliances, that experiment is necessary to progress. He therefore does not hesitate to provide the means for undertaking an optical experiment on a large scale. Let us consider its probable outcome.

In the first place, the question arises whether a sufficiently homogeneous glass disk of the required dimensions can be obtained. Our long experience with the Plate Glass Company of St. Gobain leads us to believe that no insuperable difficulty will be encountered. This old and reliable company has cast for us scores of disks, from which Professor Ritchey has made a large number of plane and concave mirrors, from the smallest sizes up to 60 inches. At present the 60-inch is receiving the finishing touches in our optical shop, and two 36-inch (0.91 m) mirrors, for testing purposes, are well advanced, in addition to several large plane and convex mirrors for the 60-inch reflector. In all of these cases the glass disks furnished by the St. Gobain Company have left nothing to be desired. The 60-inch disk, 8 inches (20.3 cm) thick, and weighing a ton, is fully equal in quality to the smaller ones. We are therefore inclined to believe, since the St. Gobain Company expresses its deliberate opinion that a satisfactory disk, 100 inches in diameter and 13 inches thick, can be produced, that they will be able to carry out the order we have given them.

As for the work of grinding and figuring, no one who has watched the progress of our 60-inch mirror would be likely to doubt Professor Ritchey's ability to accomplish this difficult task. The method of parabolizing which he has recently perfected will apply as well to a 100-inch mirror as to the 60-inch. It eliminates the necessity of any hand-work, and has already yielded a paraboloidal figure so perfect that almost any other optician would be more than contented with it. Professor Ritchey rightly believes, however, that a still higher degree of perfection will be worth attaining, since its advantages will be felt under the most perfect atmospheric conditions. I am confident that he will find no difficulty in bringing the 100-inch mirror, as well as the 60-inch, to this highest order of perfection.

The mounting should offer no great obstacles, especially as it will not be designed until the mounting of the 60-inch has been thoroughly tested on Mount Wilson. Unless I am greatly mistaken, this latter instrument will meet our best expectations. Professor Ritchey has taken the greatest pains with the design, and the co-operation of the able staff of engineers at the Union Iron Works has been most useful. The mechanical execution of the parts is admirable, and with the heavy machinery available, a mounting much larger than that required for the 100-inch mirror should be easily within the bounds of possibility. To a firm which has built some of the most powerful battleships and cruisers in our navy such a mounting would appear much less formidable than to the average instrument-maker, accustomed to a different class of work. Fortunately, the ideas of the Union Iron Works Company, as to the degree of precision required, are entirely in harmony with our own, and appear to have been met in the mounting of the 60-inch, which has just arrived in Pasadena.

The prevention of change of figure due to changing temperature should not prove a very serious problem. During the fine nights of the best observing season on Mount Wilson the temperature remains almost perfectly constant after 9 P. M. It will therefore only be necessary to maintain the mirror (or possibly the entire telescope) at approximately this temperature throughout the day, by means of suitable refrigerating machinery. In the long periods of absolutely cloudless weather the change of temperature from night to night is extremely small, so that little difficulty should be encountered on this score. If the slowly falling temperature during the early evening should prove to give trouble, the observational work might be deferred until after nine o'clock. The dome and building like those designed for the 60-inch reflector, will be so constructed that no air can enter during the day; they will also be protected by louvers from the heat of the Sun. The problem is, of course, altogether different from that encountered in the case of the Snow telescope, where the mirrors are required to give good images in spite of their exposure to direct sunlight.

Assuming that these various difficulties can be successfully overcome, it still remains a question whether the atmospheric conditions on Mount Wilson will be sufficiently good to permit the telescope to give satisfactory images. This cannot be definitely determined until after the 60-inch reflector has been used for some time. Even if it should prove, however, that only a very few nights in the course of a year can be utilized to the fullest advantage, the construction of such a telescope would nevertheless be desirable. For under the ordinary conditions, which are much finer than those in the eastern part of the United States, results of the highest value can be obtained in many classes of work, such as the photography of stellar spectra, the measurement of the heat radiation of the stars, etc. The immense amount of light which this mirror will collect should render it particularly suitable for spectroscopic work of all kinds.

It need hardly be said that the 100-inch mirror, when suitably mounted, will play a most important part in the scheme of research of the Solar Observatory. The investigation of stellar evolution, upon which we are engaged, frequently calls for adequate spectroscopic study of stars beyond the reach of existing instruments. In my work on the red stars of Secchi's fourth type, with the 40-inch Yerkes telescope, I encountered this difficulty, in spite of the great light-collecting power of that instrument. It was impossible to obtain satisfactory evidence as to the transition from solar stars to those of the fourth type. The large number of stars within the reach of a 100-inch reflector should greatly increase the possibility of finding the intermediate types, which are so important in their bearing upon the relationship of solar and red stars. This is only a single instance, but it forcibly suggests itself when considering our program of research. In other fields the large reflector should be equally valuable, especially for the photography of the numerous small spiral nebulae, the details of which should be brought out to good advantage with a focal length of 50 feet; minute study of the large nebulae, in the hope of detecting changes in their form; the study, with very high dispersion, of the spectra of bright stars, etc. The remarkable calm of the summer nights on Mount Wilson should assist materially in all of this work, since vibration of the tube, caused by the wind, would undoubtedly be a serious drawback under less favorable conditions.

No provision has yet been made for the mounting and dome. It is not known from what source funds for this purpose will come, but I believe a donor will be found by the time they are needed. Mr. Hooker's gift is very opportune, because of the fact that it permits us, now that the 60-inch mirror is nearly completed, to retain and use to the best advantage the services of the opticians trained by Professor Ritchey for our present work. The making of the glass disk, and the grinding and figuring of the various mirrors, will probably occupy about four years. Since the Union Iron Works Company will require only a year for the construction of the mounting and dome, it is evident that no funds for this purpose will be needed at present, and that the experience gained with the 60-inch reflector can be utilized in designing them.

PURCHASE OF THE SNOW TELESCOPE BY THE SOLAR OBSERVATORY

As stated in previous papers, the authorities of the University of Chicago were kind enough to loan the Snow telescope to the Solar Observatory for a period of two years. It subsequently became the opinion of all parties concerned that, in view of the very satisfactory performance of this instrument on Mount Wilson, it would be advisable to keep it there permanently. Accordingly, the Snow telescope has been purchased by the Solar Observatory, and will thus form a part of its permanent equipment. I wish to express my sense of obligation to Miss Snow, to Professor Frost, Director of the Yerkes Observatory, and to Acting President Judson and the Trustees of the University of Chicago, for the courtesies shown us in connection with the loan and sale of this valuable instrument.

SEPTEMBER 1906.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 14

Reprinted from the *Astrophysical Journal*, Vol. XXV, pp. 68–74, 1907

A VERTICAL COELOSTAT TELESCOPE[1]

By GEORGE E. HALE

One of the most difficult problems of the Solar Observatory is that of designing a telescope to meet the rigorous requirements of solar research. The distortion of mirrors, and the local disturbances of the atmosphere, caused by the Sun's heat, are obstacles more serious than any encountered in the case of night observations. The peculiar advantage of the equatorial refractor—viz., that the object glass is not seriously distorted, nor the focus greatly changed, by exposure to sunlight—is offset by the necessity of attaching all spectroscopes and other accessory apparatus to a movable telescope tube. This defect of the equatorial has greatly retarded the progress of solar research, by delaying the application of long-focus grating spectrographs to the study of the solar image.

Many important investigations require the provision of a telescope giving a sharply defined solar image, of large diameter, at a fixed position within a laboratory. The focal length of such a telescope must not change rapidly when the instrument is exposed to the Sun. The image must not rotate, and the laboratory conditions must permit the successful use of the largest and most powerful spectrographs and spectroheliographs.

The Snow telescope meets most of these requirements in a very satisfactory manner. Under suitable atmospheric conditions the large solar image given by it is so sharply defined as to resemble a steel engraving. The five-foot spectroheliograph has permitted excellent photographs of this image to be obtained with the lines of calcium, hydrogen, iron, and other substances. A Littrow spectrograph of eighteen feet focal length has provided the means of photographing the spectra of sun-spots, and the results have proved very useful in the study of the strengthened and weakened lines. The one difficulty with the Snow telescope is the distortion of the image and the change of focus when the mirrors are exposed for some time to the Sun. This is not serious in our present work, since short exposures suffice in photographic observations with the five-foot spectroheliograph and the Littrow spectrograph. But if long exposures were needed, as in the case of a thirty-foot spectroheliograph, the change of focus during the exposure would be a serious obstacle. Various ways of overcoming this difficulty have suggested themselves, and one of these will shortly be tried. But since the Snow telescope is fully occupied with its present work, for which it has proved to be well adapted, it has become necessary to devote special attention to the design of a second coelostat telescope. The daily program of observations keeps the Snow telescope so constantly in use that all new work, such as the application of the thirty-foot spectroheliograph, and the study of sun-spot spectra with the remarkable eight-inch grating, recently made and offered for our use by Professor Michelson, must be deferred until the new telescope is completed.

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[1] *Contributions from the Solar Observatory*, No. 14.

A careful study of the requirements of solar research on Mount Wilson has led me to the following conclusions:

1. A coelostat should be employed, in preference to any form of heliostat or siderostat, since it causes no rotation of the solar image.

2. The coelostat should be mounted at a considerable height above the ground, to reduce the effect of the hot air rising from the Earth.[1]

3. The ground about the instrument should be shaded, for the same reason.

4. The telescope should be best adapted for early morning and late afternoon observations, the former being the more important, because of the better definition.

5. All the mirrors employed should be completely filled with sunlight, to obviate irregular distortion.

6. The mirrors should be extremely thick, to reduce the degree of bending caused by heating.

7. The backs of the mirrors should be silvered, and exposed to sunlight, to compensate bending.

8. The beam of light, after reflection from the second mirror,

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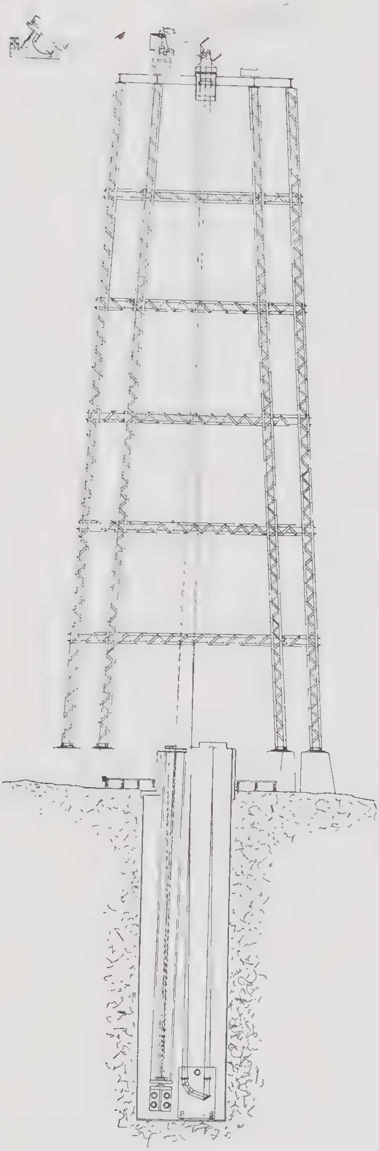
[1] See report of observations made from a tree, etc., in "A Study of the Conditions for Solar Research at Mount Wilson, California," *Contributions from the Solar Observatory*, No. 1, pp. 23, 25, 26.

PLATE XV



Vertical Coelostat Telescope

should be vertical, to reduce the danger of disturbances across the wave-front.[1]

9. The image should be formed by an object-glass instead of a concave mirror, in order to bring the focal plane near the ground, to reduce variations of focal length, to shorten the path between coelostat and image, and to facilitate the use of a large spectroheliograph.

10. The walls below the coelostat should be constructed so as to heat as little as possible, when exposed to the Sun. Other devices may also be employed to decrease the evil effects of rising currents of heated air.

11. The spectroscopic laboratory should be below ground, to insure constancy of temperature and great stability of the instruments.

The vertical coelostat telescope shown in outline in the figure, is the outcome of experience with the Snow telescope, and is intended to satisfy the conditions named above.

Two entirely independent galvanized steel towers (about 60 feet high) are required: one (in lieu of a pier) for the support of the coelostat, the other to shield the inner tower from the wind.[2] The outer tower is to be covered with canvas louvres (not shown in the sketch) similar to those used on the Snow telescope house.[3] To prevent vibrations of the outer tower from being transmitted through the ground to the inner tower, the concrete base of one tower will stand on the surface of the ground, while the foundation of the other will extend below the surface. Guy ropes will also be used where necessary. Indeed, the calm which prevails on Mount Wilson during the best observing hours of the dry season has made it seem advisable to try the experiment of using the inner tower alone at first, depending for stability on a large number of steel guy ropes. The inner tower will be used as a skeleton, without covering, so as to expose but little area. If it does not prove to be steady enough, the other tower, with louvres, will be erected later.

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[1] The advantages of a vertical beam have been pointed out by Plummer in *Monthly Notices*, **65**, 500, 1905. They have also been mentioned by Frost in a personal letter to me.

[2] President Woodward assures me, after his experience in observing from the summit of lofty wooden towers, similarly shielded, in the work of the Coast Survey, that no trouble from vibration need be feared.

[3] *Contributions from the Solar Observatory*, No. 4; *Astrophysical Journal*, **23**, 6, 1906.

The second mirror stands near the middle of the tower. It is to be elliptical in form, with major axis of 22¼ inches (56.5 cm) and minor axis of 12¾ inches (32.4 cm). Both this mirror, and the coelostat mirror (17 inches = 43.2 cm in diameter), will be 12 inches (30.5 cm thick). Experiments made by Professor Ritchey have shown that when a silvered mirror is heated by radiation, the front (warmer) surface becomes convex and the rear surface concave. By placing an electrically heated disk near the rear surface the form can be quickly restored, though the figure, when thus corrected, is not perfect. This experiment, and others involving a test of the curvature of the surfaces, show that the effect of exposing the mirror to sunlight is to produce an actual bending of the mirror. The simple expedient of greatly thickening the disk, so as to increase the resistance to bending, naturally suggested itself to me.

The second mirror is given an elliptical form, so that it may be completely filled with sunlight without undue increase in the size of the coelostat mirror. Its position in this design is such that the polished and silvered back can easily be exposed to the Sun. The angle of incidence is not ordinarily the same as that at the front surface, but the difference is partially offset by the fact that the heating effect of the beam on the face is reduced through the loss incurred by reflection from the coelostat mirror. It is hoped that the great thickness of the mirrors will render more accurate compensation unnecessary.

The coelostat stands on rails, which permit it to be moved north and south. For northern declinations of the Sun it stands north of the second mirror, for southern declinations south, and when the Sun is at the equinox the coelostat is due east or west. The arrangement shown in the figure is that employed with the low morning Sun, for which the telescope will most frequently be used. For the low afternoon Sun the coelostat is transferred, by means of its carriage (which moves easily across east-and-west rails connecting the north-and-south rails at one end) to the rails east of the second mirror. The second mirror is then rotated 180°, and the beam sent vertically downward as before. The back of the coelostat mirror will be heated, if necessary, by sunlight reflected from a large mirror, of ordinary thin plate glass, mounted just behind it. The rails are accurately planed and defined in position, so that the polar axis of the coelostat will always remain in adjustment.

The coelostat will resemble the one used on the Snow telescope, except for the much greater thickness of the mirror and some improvements in the driving mechanism.

The beam will be reflected vertically downward from the second mirror to a 12-inch (30.5 cm) object-glass, by Brashear, mounted immediately below it. The use of an object-glass, instead of a concave mirror (as in the Snow telescope), is somewhat objectionable, because of its imperfect achromatism. But in practice this is not a serious matter, and the other advantages greatly outweigh this single disadvantage. In the first place, the path of the beam between the second mirror and image, for the same focal length of 60 feet, (18.29 m) is less than half as great as in the Snow telescope, thus reducing the disturbance of the image. Again, the image is formed at a point near the ground, rather than at the top of the tower, where large spectroscopes could not be used to advantage. Finally, the object-glass can be mounted in a carriage, moving on steel balls along rails, thus providing a simple means of producing the motion of the solar image across the collimator slit of the 30-foot (9.14 m) spectroheliograph.

An electric motor, of variable speed, mounted on a pier at the ground level, will drive the photographic plate across the camera slits, and at the same time give synchronous motion to the 12-inch object-glass by means of a vertical shaft passing up through the tower. There will be three collimator slits, so that three photographs of the same part of the Sun may be taken simultaneously with the aid of different lines. The high dispersion of the spectroheliograph should permit some of the narrower dark lines to be used. The collimator and camera lenses (by Brashear) have an aperture of 8 inches (20.3 cm) and a focal length of 30 feet (9.14 m).

The prisms were ordered early in 1905,[1] but have not yet been completed, owing to the difficulty of making suitable glass of the necessary size. For this reason fluid prisms, provided with special means of stirring the liquid contents and of maintaining it at a constant temperature, may be adopted. Slight variations in the position of a spectral line, due to residual fluctuations of temperature, may be compensated by rotating the mirror in the optical train of the spectroheliograph. For guiding purposes, a line near the one in use would be held in a fixed position, just as in the analogous case of stellar photography.

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[1] It was originally intended to use this spectroheliograph with the Snow telescope.

A small change in the inclination of the mirror at the summit of the tower will cause the solar image to fall on the slit of the Littrow spectrograph, shown at the left of the spectroheliograph. Through the great kindness of Professor Michelson, which I wish especially to acknowledge, this spectrograph will contain an 8-inch (20.3 cm) plane grating, having 500 lines to the millimeter. The aperture and focal length of the objective which serves for both collimator and camera will be 6 inches (15.2 cm) and 30 feet (9.14 m) respectively. The photographic plate will be placed near the slit, as in the case of the Littrow spectrograph used with the Snow telescope. This spectrograph is intended especially for the study of the solar rotation and the photography of the spectra of sun-spots.

October 1906

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 15

Reprinted from the *Astrophysical Journal*, Vol. XXV, pp. 75–94, 1907

SECOND PAPER ON THE CAUSE OF THE CHARACTERISTIC PHENOMENA OF SUN-SPOT SPECTRA[1]

BY GEORGE E. HALE AND WALTER S. ADAMS

In a previous study[2] of more than two hundred lines photographed in the spectra of sun-spots it was shown that the lines which are strengthened in spots are, in general, strengthened in the laboratory when the vapor producing them is reduced in temperature. The same condition decreases the relative intensity of lines that are weakened in spots. In a note added to the paper it was stated that at least one of the flutings of titanium appears in our photographs of spot spectra. In the present paper we bring forward additional evidence favoring the view that most of the characteristic phenomena of sun-spot spectra are due to a reduction in temperature of the spot vapors below that of the reversing layer.

In an important paper[3] Fowler, though apparently inclined to retain his former view of a general intensification of the lines of certain elements in spots, gives some results with which ours are in good agreement. He points out that certain lines of iron, titanium, vanadium, and scandium, which are strong in arc or flame, are strengthened in spots. He also shows that many enhanced lines are weakened in spots. Fowler's general conclusion is as follows:

> The general result of the preliminary discussion is to suggest that, while the enhanced lines of some elements are usually reduced in intensity in the spot spectrum, the arc lines are intensified in accordance with their intensities in the arc-flame, thus suggesting that the additional absorption is produced by relatively cool vapors. This result was, in fact, long ago arrived at by Sir Norman Lockyer, who stated that "many of the lines seen in spots are lines seen at low temperatures (some of them in the oxyhydrogen flame), and none of them are those brightened or intensified when we pass from the temperature of the electric

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[1] *Contributions from the Solar Observatory*, No. 15.

[2] George E. Hale, Walter S. Adams, and Henry G. Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Solar Observatory*, No. 11, *Astrophysical Journal*, **24**, 185–213, 1906.

[3] *Trans. International Union for Co-operation in Solar Research*, **1**, p. 201.

arc to that of the electric spark." Such a reduction of temperature also accords well with the presence of spot bands, as already remarked by Cortie and others.

Fowler's views are thus in perfect harmony with our own, except as regards the cause of the weakening of the "enhanced" lines. On this point he writes as follows:

> It is probable that the vapors producing the enhanced lines are chiefly restricted to the higher chromospheric levels, but it is not yet clear whether the reduced intensities in spots is due to the withdrawal of these vapors from over the spot, or to the absence of a sufficiently luminous background to strongly exhibit their absorption (p. 220).

It has seemed to us that, if the strengthening of the flame lines may be accounted for by the reduced temperature of the umbral vapors, the weakening of the spark lines may equally well be attributed to the same cause. This subject, however, is still under investigation.

It is evident, from Fowler's failure to identify the titanium flutings in spot spectra, that photography may be considered to offer special advantages for the study of the fainter lines and bands.

In view of Lockyer's early observations, it is odd that he did not adopt the hypothesis that spots are regions of reduced temperature. He has long held, on the contrary, that at times of sun-spot maximum (when our spectra were photographed) the spot temperature is so high as to dissociate many of the elements represented in the solar spectrum. If, as a paper published before the appearance of our Mount Wilson results[1] indicates, he now believes that sun-spots and red stars are cooler than the reversing layer, he may have abandoned or modified his views regarding dissociation in spots.

TITANIUM FLUTINGS IN SPOT SPECTRA

In our study of the spot spectra the titanium fluting of shortest wave-length which we have as yet been able to identify with certainty is that beginning at λ 5598.0. There seems to be some evidence for the presence of two more refrangible flutings at λ 5166 and λ 5449, but it is by no means conclusive. It would, in fact, be somewhat remarkable if these were present upon our plates, since they are

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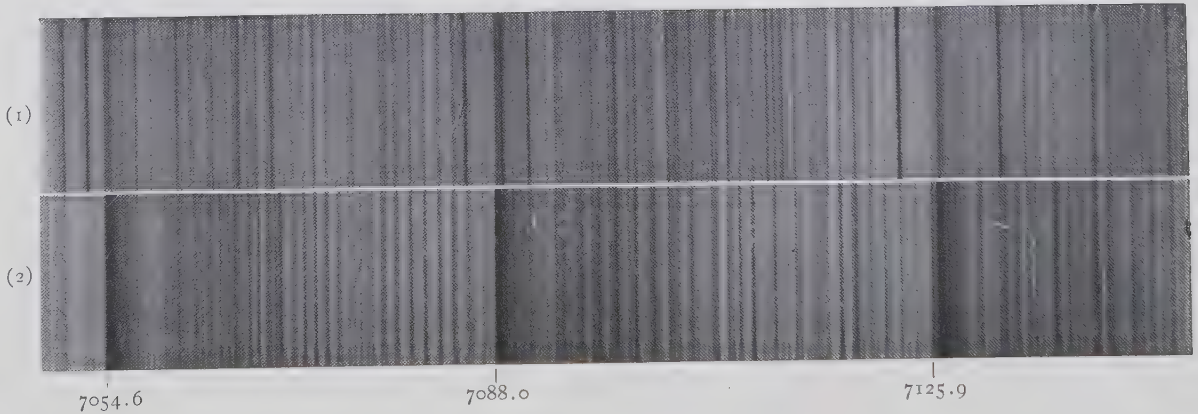
[1] But subsequent to the publication of our work at the Yerkes Observatory on the connection between spot and red-star spectra. (*Publications of the Yerkes Observatory*, Vol. II.)

PLATE XVI



Titanium Flutings in Spectra of (1) Sun-Spot and (2) Arc-Flame.

much fainter in the titanium flame spectrum than the fluting at λ 5598, which is very faint and difficult in spots.[1]

As we go toward longer wave-lengths, the successive flutings become stronger in the spot spectrum, until in the deep red they form its most characteristic feature. The fluting at λ 7055 is especially noticeable, as it occurs in a region of the spectrum in which there are but few strong lines to interrupt its continuity. A comparison of this fluting in the spot and in the flame of the electric arc (negative copy) is given in Plate XVI.

The following tables contain the results of measures of the lines in the spot and the flame spectra, and a comparison of the two with each other and with the corresponding lines in the spectrum of the disk, where such exist. It has seemed desirable to give the evidence in full, not only on account of the importance of the question of the existence of the titanium flutings in spots, but also because of the almost equally important one of their existence in the spectrum of the disk. The results given here, however, are not to be regarded as complete, nor do the coincidences shown represent by any means the total contribution of the titanium flutings to the spot spectrum in this region. The flame spectrum of titanium in the red consists of a large number of flutings and bands, which overlie one another in an extremely complex fashion and contain a vast number of lines. The spectrum of the spot is similar, and a complete comparison of the two will involve a very large amount of measurement, and belongs rather to an exhaustive investigation of the spot spectrum than to the objects of this communication. Enough is given here, we believe, to indicate the nature of the results which a complete study would furnish.

The method of procedure which we have followed has been to select the more important of the titanium flutings in the spectrum of the flame of the electric arc and to measure all lines within a considerable distance of their heads. The results are then compared with the lines measured in our photographs of spots. In order to show what proportion of the spot lines is due to titanium, a complete list is given for the regions investigated, except, of course, that the lines identified by Rowland are not included. The arrangement of the tables is as follows: The first two columns contain the wave-lengths and intensities of the lines measured in spots, the third and fourth columns the wave-lengths and intensities of lines given in Rowland's tables which may be coincident with the spot lines, and the fifth column the wave-lengths of the lines measured in the flame spectrum of titanium. We have assumed for the greater part of the spectrum the value of 0.05 tenth-meters as the largest discordance which may exist between lines coincident in spot, disk, and flame, our measures of the stronger lines identified by Rowland indicating ranges of about this amount. In the extreme red this value becomes slightly larger, the character of the lines preventing such accuracy of measurement as can be attained in the more refrangible regions.

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[1] The head of this fluting has been measured upon numerous plates. Only two plates, however, and these taken under exceptionally good conditions, show the fine lines satisfactorily. The fluting beginning at λ 5604.00 may be present in spots, but the existence of other lines in this region leaves the matter doubtful.

An analysis of these tables gives the following results:

Total number of spot lines	234
Coincident with *Ti* lines	152

Thus about 65 per cent. of the total number of spot lines have corresponding lines in the band spectrum of titanium.

Number of spot lines with *Ti* coincidences which have possible coincidences in the disk spectrum		42
Identified by Rowland or not coincident with *Ti* lines	19	
Strong lines of *Ti* or other elements	6	25
Number of lines in disk coincident with *Ti* lines		17
Number of spot lines with no *Ti* coincidences		82
Number of coincidences in disk for these		36

This summary leads to the important conclusion that 43 per cent. of the spot lines with no coincidences in the *Ti* band spectrum, and but 11 per cent. of those with such coincidences, have corresponding lines in the disk. Since the latter quantity is no larger than could be accounted for by accidental coincidences within the limits of accuracy of the measures, the conclusion is justified that the titanium flutings are not present in the spectrum of the disk. This conclusion is greatly strengthened by the fact that of the nine heads of flutings which have been measured in spots and in the flame, and which are conspicuous as compared with the remainder of the lines of the band spectrum, only one has a possible counterpart in the

PLATE XVII

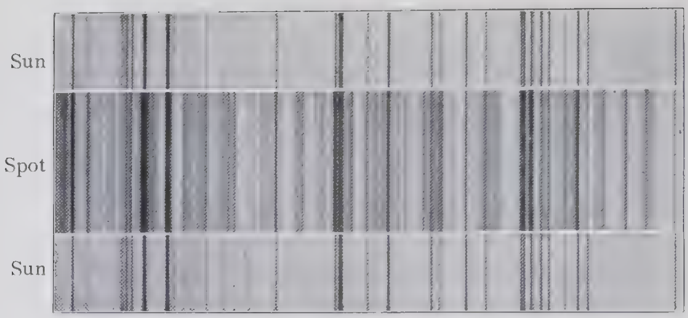

Fig. 1

Region λ 5040–λ 5090

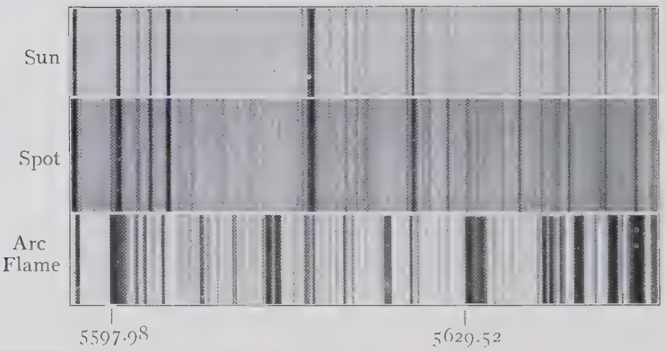

Fig. 2

Titanium Flutings in Spot and Arc Flame.

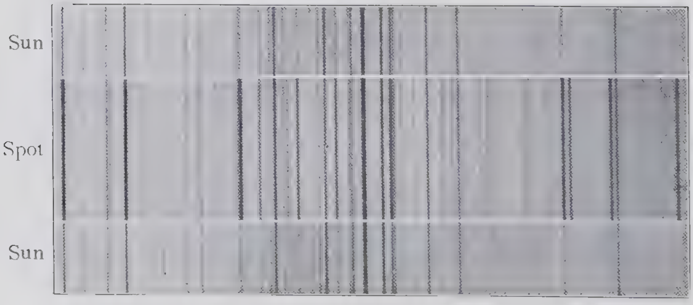

Fig. 3

Region λ 5680–λ 5740

Photographs of Sun-Spot Spectra.

TABLE I

Comparison of Titanium Flutings with Spot and Solar Spectra

Spot		Sun		*Ti*	Notes
λ	Int.	λ	Int.	λ	
5597.98	1	...	.....	.99	1st head
5600.79	000	...	.....	.80	
5608.48	000	.52	000	.49	
5698.74	000	...	.....	.74	
5609.04	000	...	.....	.02	
5609.31	000	...	.....	.33	
5611.02	00	...	.....	.02	
* * * *	* *	* *	* * *	* *	
5629.52	0–1	...	.....	.52	2d head
* * * *	* *	* *	* * *	* *	
6158.84	0–1	.89	000	.84	1st head
6159.38	0	...	.....	.36	
6164.86	00	...	.....	.9	
6168.00	00–0	...	.....	.00	
6171.41	0	.44	0000	.40	
6172.18	1	.16	000	.10	
6174.41	1	...	......	.46	
6184.72	0	...	......	.65	
6187.82	0	...	......	.87	
6189.02	1–2	...	......	88.92	
6189.58	1	.59	0000 N	...	*V* 6189.58
6190.12	1	...	......	.117	
6192.42	0	...	......	.39	
6193.02	0–1	...	......	.01	
6193.56	0–1	...	......	.56	
6194.35	0	...	......	.30	
6195.31	00	...	......	.33	
6195.69	0–1	.66	0 N	...	
6197.29	0	...	......	.32	
6197.88	0–1	...	......	.91	
6198.68	1–2	...	......	.64	
6199.84	1	.72 .98	00 0000	.84	
6201.20	0–1	.18	000	.18	
6201.94	0	...	......	.94	
6202.58	1	...	......	.59	
6202.96	0	...	......	...	
6203.38	1	...	......	.38	
6206.60	1	...	......	.59	
6208.08	0–1	...	......	.08	
6208.65	0–1	...	......	08.97	*Ti* line double or triple
6209.17	1	...	......		
6209.55	0	...	......		
6210.18	2	...	......	.17	
6210.89	5	.90	000 N	...	*Ti* line at 6211.02, which is probably included in this
6211.88	0	...	......	.91	
6212.15	0	...	......	...	
6212.48	0	.48	0000	.45	
6214.07	2	.08	*V* 000	.03	
6214.43	0	...	......	...	*Cr* line at 6214.41
* * * *	* *	* *	* * *	* *	
6262.01	0	...	......	61.99	

TABLE I—*Continued*

Spot		Sun		*Ti*	Notes
λ	Int	λ	Int.	λ	
6262.52	0	...	......	.50	
6262.90	0	...	......	63.20	*Ti* line double
6263.45	0		......		
6263.99	1	...	......	.97	
6264.82	1	...	......	.84	
6266.14 66.51	2	... .55	 000	.16 ...	*V* 6266.54
6269.00	2	68.82 69.08	0000 V 000 N	...	
6274.86	4	.87	00	...	*V* 6274.89
6276.40	0	.45	0000 N	...	
6284.36	0	...	......	...	
6285.34	4	.38	V 00 N	...	
6286.17	1	...	......	...	
6286.98	0–1	87.01	0000 N	...	*V* 6287.02:*Cr* 6286.95
6289.23	00	...	......	...	
6289.70	2	.61 .79	A (O) 1 0000	...	Spot line broad
6292.11	0	...	......	.13	*V* line at 6292.09
6293.09	6	.03 .17	*V* 000 A (O) 3	.09	
6296.78	4–5	...	......	.82	
6297.25	0	...	......	...	
6300.58	0	.54	000	.62	
6300.93	0–1	.90	000	...	
6303.97	4	.98	000 N	.98	Strong line of *Ti*
6305.03	00	.07	0000 N	...	
6305.90	10	.88	0000	... .77	Spot line very broad. Due in part to strong *Ti* line 6305.77
6307.21	0	...	......	...	*Cr* 6307.19
6307.59	0	...	......	.55	
6307.99	0	...	......	08.01	
6308.52	1	...	......	.47	
6309.72	0–1	...	......	...	*V* 6309.74
6311.06	1	.06	0000	...	
6312.46	3	.46	00 N	.46	Strong line of *Ti*
6313.18	1–2	...	......	.14	
6313.72	0–1	...	......	...	
6314.47	1	.45	A (O) 0	.42	
6316.62	1	.51 .82	A(wv)0000N 0000	.54 ...	Spot line very broad
6322.02	0–1	...	......	...	
6323.53	1	...	......	.51	
6324.70	0	.71	A (O) 00	.74	*V* line at 6324.74
6325.39	2	.38	0000	.34	
6326.34	0–1	...	......	...	
6327.11	1	...	......	.13	
6331.80	1	...	......	...	
* * * *	* *	* *	* * *	* *	
6651.62	2	...	......	.56	1st head
6652.32	00–0	...	......	.30	
6653.19	00	.22	0000	.24	
6653.80 54.89	1	...	......	54.44	Broad patch in both spot and *Ti*

TABLE I—*Continued*

Spot		Sun		*Ti*	Notes
λ	Int.	λ	Int.	λ	
6655.21	00	...	......	...	
6656.67	0–1	.62	0000	.67	
6657.25	0–1	.20	000 N	.27	
6657.99	0–1	...	......	.96	
6658.58	0	...	......	.54	
6659.20	0	.16	0000	...	
6660.78	0–1	.83	0000	...	
6661.37	1	.32	*Cr* 00	.32	
6662.08	00	62.01 ...	0000 N	61.99 ...	Broad in spot
6662.67	0	...	......	...	
6664.83	1	...	......	.79	
6665.55	1	...	......	.52	
6666.63 .77	0	... .78	...... 000 N	.70	
6667.24	00	...	......	...	
6668.03	0	...	......	.02	
6668.63	00	.64	000 N	...	
6669.06	0	.04	0000 N	.01	
* * * *	* *	* *	* * *	* *	
6681.11	1	...	......	.11	2d head
6681.65	00	...	......	.62	Practically a band in spot
6682.34	00	...	......	.30	
6682.91	00	...	......	...	
6683.63	00	...	......	.65	
6684.96	00	...	......	...	
6686.10	0–1	...	......	.11	
6687.78	1	.75	0000	...	
6688.28	00	...	......	...	
6689.06	0	...	......	...	
6689.59	00	...	......	...	
6690.14 91.44	1–2	...	......	...	A broad band in spot
6691.91	0	...	......	.95	
6692.83	00	...	......	.80	
6693.62	0	...	......	.61	
6694.58	00–0	...	......	.56	
6695.53	00	...	......	.51	
6697.19	00	...	......	...	
6698.12	00	...	......	.10	
6698.87	2	.91	0	.84	
6699.90	0	...	......	.92	
6700.36 6700.82	00 00	... ...	....	.64	*Ti* line double
6701.67	0–1	.62	000	.65	
6704.82	00	...	......	.86	
6705.85	0	.75 .94	0000 0000	.86	
6706.80	0	...	......	.81	
6707.39	00	...	..	...	
6708.13	4	.18	0000	...	*Ca* 6708.15
6709.23	0	.23	0000N	.24	
6710.57	1	.57	0	...	
6711.49	0	.53	0000	.52	

TABLE I—*Continued*

Spot		Sun		*Ti*	Notes
λ	Int.	λ	Int.	λ	
6711.98	00	...	......	...	
6712.57	00	...	......	...	
6713.09	0	...	......	.14	
6714.30	1	...	......	.25	
6714.80	00	...	......	.82	
6715.59	2	.64	1	.54	
6716.12	00	...	......	.17	
6716.98	0	....	......	.95	
6718.49	00	...	......	...	
6719.84	1–2	.88	000 N	.86	Strong line of *Ti*
6720.49	00	...	......	...	
6721.18	00	...	......	.18	
6721.66	00	...	......	.65	
6722.24	2	...	......	.24	
6722.75	00	...	......	.78	
6723.74	00–0	...	......	.76	
6724.20	00–0	...	......	.19	
6724.60	00	...	......	...	
6725.27	0	.22	0000	...	
6725.89	0	...	......	.86	
6726.30	00–0	...	......	.26	
6727.30	00	...	......	...	
6728.53	1	...	......	.48	
6729.26	1	.27	00	.22	
6730.05	00	.00	000 N	...	
6730.56	00	.56	000 N	.55	Fairly strong *Ti* line
6731.08 31.83	0	...	......	.56	Broad patch in spot
6731.96	..	...	......	.94	Bright streak in spot: dark space in *Ti*
6732.83 34.00	1–2	...	......	... .06	Broad band
6735.31	00	.28	0000	...	
6735.79	0	...	......	.77	
6736.36	0	...	......	.23	Spot line is double: *Ti* line forms one component
6737.28	0	...	......	.30	
6738.07	0	...	......	.07	
6738.70 39.79	2	... .78	 0	.65 ...	Broad band in spot
6740.57	00	...	......	...	
6740.82	0	...	......	.83	
6741.72 42.44	2	...	......	42.12	
* * * *	* *	* *	* * *	* *	
7054.60	2	...	......	.65	Strong head in both spot and *Ti*
* * * *	* *	* *	* * * *	* *	
7069.32	0	.35	0000 N	...	
7069.73	00	...	......	...	
7070.40	1–2	...	......	.37	
7071.35	1	...	......	.30	
7072.29	1–2	...	......	.27	Spot line includes solar 7072.13
7072.75	00	.72	000	...	
7073.27	1	...	......	.29	

TABLE I—*Continued*

Spot		Sun		*Ti*	Notes
λ	Int.	λ	Int.	λ	
7074.18	00–0	. . .	. . . . . .	.33	
7074.54	00	. . .	. . . . . .		
7075.15	0	.19	0000	. . .	
7076.18	0	. . .	. . . . . .	. . .	
7076.72	00–0	. . .	. . . . . .	. . .	
7077.23	00	. . .	. . . . . .	.15	Lines poor in both spot and *Ti*
7077.99	1–2	. . .	. . . . . .	78.10	
7078.29	0		. . . . . .		
7079.24	2	. . .	. . . . . .	.26	
7080.47	1	. . .	. . . . . .	.47	
7081.68	1	. . .	. . . . . .	.69	
7082.96	1–2	. . .	. . . . . .	.96	
7084.25	1–2	.24	000 N	.24	Fairly strong line of *Ti*
7086.66	00	.59	0000	. . .	
7087.90	1–2	. . .	. . . . . .	88.00	2d head of fluting
7089.28	00	. . .	. . . . . .	. . .	
7091.41	00	.43	0000	. . .	
7092.20	00	.22	000 N	. . .	
7092.85 93.65	2	. . .	. . . . . .	93.3	Broad band in spot; very broad, hazy, and poor in *Ti*
7094.79	00	. . .	. . . . . .	95.00	
7095.16	00		. . . . . .		
7096.12	0	.14	000	. . .	
7096.63	0	.66	0000	. . .	
7097.50	0	. . .	. . . . . .	. . .	
7099.19	0	.22	0000 N	. . .	
7099.83	1	.81	0000 N	.77	
7101.31	1	. . .	. . . . . .	.35	
7102.63	1–2	.56	000 N	. . .	
7103.26	0	. . .	. . . . . .	. . .	
7104.63	0	. . .	. . . . . .	.65	
7105.02	00	. . .	. . . . . .	. . .	
7106.36	1	.43	A ? 000Nd ?	.59	
7106.77	1	. . .	. . . . . .		
7108.13	00	.19	0000 N	. . .	
7108.75	0	. . .	. . . . . .	. . .	
7109.91	0	. . .	. . . . . .	.87	
7110.66	00	.70	0000 N	. . .	
7111.75	1	.73	A 000 N	.73	
7112.87	00	. . .	. . . . . .	. . .	
7113.91	00	.87	0000	. . .	
7116.29	0	. . .	. . . . . .	. . .	
7117.34	1–2	. . .	. . . . . .	.37	
7118.52	1–2	.55	A 1	. . .	Spot line probably double
7119.21	00	.25	0000	. . .	
7119.93	00	.96	000 N	20.00	
7120.16	00	. . .	. . . . . .		
7120.43	00	. . .	. . . . . .	. . .	
7121.21	0	. . .	. . . . . .	.25	
* * * *	* *	* *	* * *	* *	
7125.89	2	. . .	. . . . . .	.88	3d head of fluting

spectrum of the disk. It seems certain, therefore, that the temperature of the reversing layer is normally too high to admit of the presence of the band spectrum of titanium.

SPARK[1] LINES IN THE RED

Though our comparison of spot lines with the spectra of the various elements is as yet very incomplete, and we have no plates extending to wave-lengths greater than λ 6700 for any except titanium,

IRON

	Enhancem't in Spark	Intensity in Sun	Intensity in Spot	
6042.32	1	*Fe* 3	2	
6103.40 .51	1–2	*Fe* 4 — 1	4	
6147.95 48.04	3	— 2 *Fe* 3	3	
6149.46	3	— 2	0	
6238.60	3	— 2	0	
6247.77	5	— 2	00	
6315.52	1–2	*Fe* 2	1	
6380.96	1	*Fe* 4	1	Rowland's intensity too high. Complicated in spark by air line
6417.13	2	*Fe?* 1	00	
6420.17	1	*Fe* 4	2–3	
6456.60	5	— 3	0–1	
6516.31	1–2	— 2	00	
6569.46	1–2	*Fe* 5	4	Complicated in spark by air line
6627.80	1–2	*Fe?* 0	00	
6663.49 .70	1	— 1 *Fe* 3	3–4	

TITANIUM

6491.80	2	— 1	00–0	

NICKEL

6119.97	1	*Ni* 0	00	Difficult in spot on account of *V* 6119.74
6125.24	2	— 1	00–0	
6130.34	1	*Ni* 1	0	

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[1] Since the beginning of this investigation, we have been troubled by a question of nomenclature. Lockyer has applied the appropriate name "enhanced line" to a

some results already found for the lines enhanced in the spark, and for a few lines strengthened in the flame spectrum, are of sufficient interest to warrant their inclusion here.

The following list includes the more important of the spark lines of iron, titanium, and nickel, and indicates their behavior in spots.[1] The amount of enhancement in the spark is given on a scale of 0 to 5.

The list on the preceding page affords strong additional evidence for the conclusion that spark lines are weakened in the spectra of spots.

FLAME LINES IN THE RED

In view of the importance of accurate determinations of changes in line intensities in passing from the core of the electric arc to the flame, it has seemed desirable to take up this side of the investigation with a photometer especially adapted for the purpose. Accordingly, we have as yet made no systematic examination of the lines strengthened in the flame for the red region of the spectrum. A few cases, however, are so striking that they are deserving of comment. The following table indicates the behavior in this regard of two lines of calcium and two lines of sodium. The amount of strengthening in the flame as compared with the core of the arc is on a scale of 0 to 5.

line that is strengthened in the spark, as compared with the arc, and this designation is now generally used in the literature of spectroscopy. No suitable name has been suggested for lines that are strengthened in the flame of the arc, where the "enhanced lines" are weakened. In any event, confusion is likely to result from the fact that the lines which have always been regarded as characteristic of sun-spots—those which are more conspicuous in the spot than in the solar spectrum—are not "enhanced" lines. On the contrary, they are lines that are strengthened in the flame; the "enhanced" lines are weakened in spots. In the present paper we have thought best to adopt the old terms "spark line" and "flame line" for lines strengthened in the spark or flame, respectively. It is, of course, well understood that spark lines do not exist exclusively in the spark, or flame lines in the flame. The intensity of spark lines increases as the temperature rises, while that of the flame lines increases as the temperature falls.

[1] As the question of impurities has not yet been fully investigated, some of these lines may arise from foreign sources, though they would still seem to belong in the list of spark lines.

CALCIUM

	Strengthening in Flame	Intensity in Sun	Intensity in Spot
6573.03	5	*Ca?* 1	8
6708.18	4	0000	4[1]

SODIUM

6154.44	2	*Na* 2	5–6
6160.96	3	*Na* 3	5

The two calcium lines given above show the largest increase of intensity in passing from the core of the arc to the flame of any lines which we have encountered. The remarkable degree to which they are affected in spots also makes them conspicuous among the spot lines.

MOTION OF SPOT VAPORS IN THE LINE OF SIGHT

The importance of the question of the motion in the line of sight of the spot vapors as bearing on any theory of spot structure, is of course, very great, and has been kept in mind in the investigation of our observational material. In the method which we have adopted of photographing spot spectra it is necessary to make the exposures on spot and disk separately, occulting one while the other is being photographed. For this purpose an occulting bar is moved across the slit by means of a rack and pinion, as in most stellar spectrographs. Accordingly, the danger of errors arising from instrumental sources should not be great.

The study of the plates has led to the conclusion that there is, as a rule, very little motion in spot umbrae. Out of eighty plates of eleven spots only two gave any reasonably certain displacements of the spot lines, and even in these two cases the values were close to the limit of accuracy of the measures. In both instances the motion was directed downward, and amounted to about 0.2 km a second. In one case, moreover, the motion was certainly temporary, since plates of the same spot taken on the following day gave no displacements whatever. The general conclusion, then, seems to be justified that the vapors forming the umbra of a well-developed spot are normally nearly at rest, with perhaps some presumption of a slow downward drift. This result is in agreement with that found by Mitchell from the study of a large number of spots during 1904–5. He says: "Line-shifts in the spot-spectrum, with the exception of those due to hydrogen, are very rare."[1]

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[1] It is not certain that this line is due to calcium, as it appears strongly on plates of several other elements. It is in every case greatly strengthened in the flame.

EFFECT OF DENSITY

The suggestion has been made that the relative intensities of lines observed in spots and in the laboratory may be due to the increased density of the vapors producing them. To test this question, the following experiments have been made in our spectroscopic laboratory by Dr. Olmsted.

The spectrum of a 30-ampere arc, between iron poles, was compared with that of a 2-ampere arc, between carbon poles containing only a trace of iron. The changes in the relative intensities of the lines were similar to those observed in passing from the ordinary solar spectrum to that of sun-spots. Moreover, a 2-ampere arc between iron poles gave the same spectrum as the 2-ampere arc between carbon poles, with but little iron present.

A spark between iron poles, with no self-induction, was compared with a spark between one iron and one carbon pole, with self-induction to cut down the temperature. The changes of relative intensity were those observed in all other cases when the temperature is reduced. Two carbon poles, with a small amount of iron filings present, and two iron poles, both with self-induction, gave the same relative intensities of the lines.

Similar experiments were tried with manganese and calcium, in both the spark and the arc. In all cases the relative intensities of the lines seemed to depend simply upon the strength of the current, or the amount of self-induction, and to be entirely independent of the density of the radiating vapor.

THE TEMPERATURE OF SUN-SPOTS

The presence of the titanium flutings in spots, and their apparent absence from the ordinary solar spectrum, strongly confirm the view that the umbral vapors are cooler than those of the reversing layer.

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[1] *Astrophysical Journal*, **22**, 38, 1905.

It is not yet certain that these flutings are due to the oxide, but they presumably represent a molecule that is dissociated at high temperatures. The fundamental differences between line and band spectra—for example, the fact that flutings are unaffected by pressure or by a magnetic field—are generally held to indicate that they arise from different aggregations; in short, that lines represent the atom, while bands represent the molecule.

In our laboratory experiments the strengthening of flame lines and the weakening of spark lines have always appeared to be associated with reduction of temperature. Crew's work has shown that rapid change of potential is an effective means of strengthening spark lines, but it almost certainly involves a momentary increase of temperature, and in any case cannot be considered the only possible mode of altering the relative intensities. The theoretical considerations so ably summarized by Crew in his recent address before the American Association[1] seem to favor the view that the relative intensities of spectral lines are more easily influenced by some electrical cause than by change of temperature. But how can the results of our experiments with so many different sources be accounted for in this way? We fail to see, for example, how electrical causes could have operated in our furnace, especially after the arc, which played on the *outer* walls of the carbon tube containing the metal, had been extinguished. It seems almost certain that in this case the relative intensities of the lines were determined by the temperature, or by chemical action, which might be a function of the temperature. The range of temperature obtainable in our furnace was hardly sufficient to produce unquestionable changes in the relative intensities of lines, though there seem to be some cases of this kind in the case of chromium. Pending the continuation of this work, we cannot claim to have done more than to prove that the changes of relative intensity from a 30-ampere to a 2-ampere arc, and from core of arc to flame, resemble those from core of arc to furnace. However, the flame is undoubtedly cooler than the core of the arc, and in the furnace the temperature was too low to melt titanium. Moreover, the well-known changes in the relative intensities of the calcium lines, in passing from the Bunsen burner to the oxyhydrogen flame, certainly indicate that temperature is quite as competent as change of potential to produce these phenomena.

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[1] *Science*, January 4, 1907.

The simplest way to account for the relative intensities of lines in the spectra of sun-spots and third-type stars is to assume that reduced temperature in these sources is the effective cause. For, on the one hand, the presence of the titanium flutings, which consistently rise and fall in intensity with the flame lines in all of our sources, and are absent from the solar spectrum, leaves little doubt that the vapors in sun-spots and third-type stars are cooler than the corresponding vapors in the reversing layer. On the other hand, laboratory experiments have shown that changes of temperature may produce, either directly or indirectly, just such spectral phenomena as those here involved. It therefore seems entirely unnecessary to assume that electrical phenomena, or other such causes, are at work, though their operation is not necessarily excluded.

Although we are thus inclined to regard the relative intensities of spot lines as resulting from reduced temperature, we by no means consider this cause competent to explain the many peculiarities exhibited by spot spectra. The existence of winged lines, for example, may depend upon the density and perhaps upon the level of the corresponding vapors. Further reference to this question is made below. A more complete investigation, however, will demand much work in the future.

STRATIFICATION OF THE VAPORS IN SUN-SPOTS

We now pass to the difficult task of examining a few of the complex details of spot spectra, for the purpose of interpreting them in accordance with some rational view of sun-spot structure. We are called upon to account for the following phenomena, among others perhaps equally important:

1. The gradual decrease, as we proceed toward shorter wave-lengths, in the amount by which spot lines are affected, and the close agreement in the ultra-violet of the spot spectrum with the solar spectrum.

2. The presence in spots of the strong and sharply defined lines of the titanium line spectrum, together with the faint flutings of the band spectrum.

3. The fact that all of the sodium lines, about 80 per cent. of the calcium lines, and about 25 per cent. of the chromium, iron, and manganese lines are accompanied by wings, while none (or very few) of the lines of titanium or vanadium are thus affected.[1]

4. The reversals of spot lines observed by Young and Mitchell.

Although no complete discussion of these points can be attempted until more laboratory work has been done, their brief consideration at the present time may aid to clear the way for further investigations. The great similarity between the spot and solar spectrum in the ultra-violet may be regarded as the maximum development of a tendency which has already become very marked in the violet region. The gradual decrease in the amount by which titanium and vanadium spot lines are affected, as we pass from the yellow through the blue to the violet, and the decrease in the number of strengthened lines of iron in the blue and violet, are strong indications of such a tendency. The changes in the relative intensities of the lines observed in the laboratory show no such marked falling-off in the more refrangible region. For this reason it seems probable that many of the spot phenomena depend upon the level of the umbral vapors in the solar atmosphere.

In our previous paper we made the purely tentative hypothesis that the gradual weakening of the spot spectrum and its replacement by an almost unmodified solar spectrum in the ultra-violet might be attributed to the presence of the ordinary reversing layer over the umbral vapors. The absorption and scattering of the more refrangible spot radiations within this layer, and especially within the spot itself, would greatly decrease their intensity, while the superposed reversing layer would produce the ordinary solar spectrum. However, the difficulty of accounting for a condition of affairs in which the reversing layer, undiminished in temperature (as indicated by the unchanged relative intensities of its lines), actually overlies the umbra and penumbra, is very great. It would seem that the temperature of vapors overlying a sun-spot must be lower than that of the corresponding vapors in the reversing layer above the photosphere, both because of the absence of strong convection currents, and because of the diminished radiation from the spot, due to the absorption and scattering of the radiation proceeding from below the umbra and the comparatively low temperature of the spot vapors. Our measures of the sun-spot lines, as explained elsewhere, show very few evidences of motion in the line of sight. In the instances when motion was detected it was directed downward. This result would be in harmony with our knowledge of other spot phenomena. It is a well-known fact, for example, that eruptions rarely or never occur in the umbra, but almost invariably at a point outside of the penumbra or in a "bridge." It would consequently appear improbable that convection currents, such as offer visible evidence of their presence in the photosphere, are to be regarded as existing in the umbra. If the umbral vapors overlie the photosphere, convection currents may possibly rise from the interior below them. Their effect upon the temperature of the region above the umbra, however, would certainly be greatly diminished by the strong absorption and scattering of the spot vapors.

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[1] These figures were derived from a study of over 400 of the strengthened lines in the region from λ 4800–λ 7300. If wings could be seen on the fainter lines, these percentages would doubtless be modified.

It is thus difficult to see how the unchanged reversing layer can exist over sun-spots. How, then, are we to account for the presence of the ordinary solar spectrum in the ultra-violet region? We have shown in previous papers that the relative brightness of the umbra as compared with the photosphere is much smaller in the violet than in the red. At λ 4000, for example, the spot spectrum must be exposed about eleven times as long as the spectrum of the disk, in order to get a negative of equal intensity, while in the yellow an exposure six times as long will suffice to give such a result.[1] The long exposure required in the violet for the spot spectrum has suggested the possibility that two principal sources, from which a solar spectrum might be derived, must be taken into account:

1. Sunlight scattered in the earth's atmosphere.
2. Light from the photosphere, brought upon the slit by atmospheric disturbances during the exposure.

Sunlight scattered by small particles lying above the umbra (such as produce the solar spectrum observed in the inner corona), and diffuse light in the spectroscope, may also be involved, but probably in very small degree.

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[1] The ratios were incorrectly given in our previous paper.

It is easy to determine the approximate intensity of the scattered light in our atmosphere. Photographs of the spectrum of the sky near the sun, taken for this purpose, showed that under the conditions existing at the time the sky spectrum at λ 4000 was about one-fortieth as bright as the spectrum of the center of the sun's disk. Our observations indicate the presence of certain spot lines, and consequently a very appreciable value for sun-spot radiation, much farther to the violet than λ 4000. At present we have a considerable number of lines in the ultra-violet reaching as far as λ 3662, and under the finest conditions of definition of the solar image this limit might perhaps be extended farther. In this region the intrinsic brightness of the sky would be appreciably greater than at λ 4000, and, in the longer exposure required to photograph the spot spectrum, the sky spectrum would appear on the plate with considerable intensity. In the less refrangible region of the visible spectrum, however, it would be much fainter, and perhaps hardly perceptible, partly because of its smaller intrinsic brightness, and partly because the exposure required for the spot is relatively much shorter than in the violet.

The effect of the photospheric light which enters the slit, because of the unsteadiness of the solar image, must always be appreciable in exposures of any considerable length. The rapid decrease in the exposure time required to photograph the spectrum of the umbra of a spot, when the definition of the sun's image becomes poor, is excellent evidence of the importance of this fact. Among other causes which would tend to introduce photospheric light into the spot spectrum would be astigmatism, due to distortion of the mirrors by heating; change of focal length during the exposure, resulting from the same cause; and unsteadiness of the spot image upon the slit, due to imperfect guiding.

The combined effect of these various causes would undoubtedly account for the presence of an ordinary solar spectrum in the ultra-violet region of spot spectra. Whether its intensity would be as great as the observed intensity cannot be certainly determined until further quantitative studies have been made.[1]

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[1] For an interesting discussion of these questions, which has reached us since the above was put in type, see Newall, *Monthly Notices*, January 1907.

In seeking to account for the phenomena enumerated (2) to (4), pp. 15 and 16, let us tentatively make the hypothesis that the minimum temperature and the maximum density of the spot vapors occur in the lower part of the umbra. We know little or nothing as to the nature of the radiation which proceeds from the photosphere or from any other source that may underlie the umbra. In any case, however, the intensity of this radiation must be greatly diminished by absorption and scattering in its transmission through the spot. The faintness of the wings accompanying so many of the lines, and the greater frequency of the winged lines in the less refrangible region, would seem to indicate that the radiation of the vapors which are dense enough to produce these wide wings must proceed from a very considerable depth, and thus be subject to strong absorption and scattering, which should be most marked in the more refrangible region. Again, we have the case of the titanium spectrum, in which the flutings are faint while the lines are strong and well-defined, in no instances (or very few) being accompanied by wings. The band spectrum, according to the generally accepted view, is due to the molecules, which will be most numerous in the region of lowest temperature. It should consequently be subject to more absorption and scattering than the line spectrum, and therefore be comparatively faint. Moreover, the flutings should rapidly grow fainter in the more refrangible region, which is the case.

The line spectrum, originating for the most part in a region of higher temperature, where the vapor is less dense, should give sharp lines, without wings. Comparing the titanium spectrum, therefore, with the spectrum of sodium, iron, or any other metal of low melting-point, we may say that the spot temperature is low enough to produce a band spectrum only in the case of so refractory a substance as titanium; whereas in the case of the other metals, the line spectrum is produced throughout the entire depth of the spot vapors.

If this purely tentative hypothesis be sound, vanadium should behave much as titanium does, on account of its high melting-point. Hitherto, however, we have not been able to produce a vanadium band spectrum in the laboratory, or to identify it in spots. We are continuing our investigations on this subject in the hope of making the test.

The hypothesis that the temperature of the spot vapors is higher in their upper part provides the simplest way of accounting for the existence of bright reversals of some of the spot lines, observed by Young and Mitchell. The question whether the lines will be reversed or not depends upon the temperature and density gradients of the vapors, just as in the case of the electric arc. If a sufficient difference of temperature exists, and the upper vapors are dense enough, reversals will occur. It is evident, however, that this subject will require much further study, made with special reference to the individual peculiarities of the reversed lines.

JANUARY, 1907

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 16

Preprinted from the *Astrophysical Journal*, Vol. XXV (June), 1907

THE HELIOMICROMETER[1]

By GEORGE E. HALE

The measurement and discussion of photographs of the sun made with the spectroheliograph involve a large number of processes, some of which have been satisfactorily worked out, while others are still under consideration. Up to the present time special attention has been devoted to the following points:

1. The measurement of the heliographic positions of flocculi, with reference to the determination of the solar rotation.

2. The measurement (with the monocular micrometer of the Zeiss stereocomparator) of the relative distances from the center of the sun of corresponding points in the calcium (H_2) and hydrogen ($H\delta$) flocculi, with reference to the relative level of these objects.

3. Comparative studies, with the same instrument, of the forms of flocculi, as photographed with various lines.

4. Photometric determinations of the relative brightness, at various distances from the sun's center, of the flocculi and the adjoining photosphere, as bearing on the level of the flocculi and the absorption of the solar atmosphere.

5. Photometric measurements similar to (3), but especially adapted for the determination of the level of sun-spots.

6. Stereoscopic studies of the flocculi.

7. Studies of the flocculi with a kinetoscope, with reference to their changes in form.

8. The measurement, by a photometric method, of the areas of flocculi in regions ten degrees square, for the study of variations in the solar activity.

Spectrographic studies have also been made, particularly of the hydrogen and calcium lines, for the purpose of interpreting the spectroheliographic results.

The present paper deals with the measurement of heliographic positions; the other methods of measurement and reduction will be described later.

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[1] *Contributions from the Solar Observatory*, No. 16.

THE HELIOMICROMETER

The determination of the heliographic positions of sun-spots, as carried on at Greenwich, involves the measurement of their polar co-ordinates, and a simple calculation, facilitated by the use of tables. As the average number of spots on each photograph is small, only a moderate amount of computing is required, and the method has apparently proved satisfactory after many years of service. For the flocculi the case is different. The average number of flocculi suitable for measurement on a single plate may reach forty or fifty, thus involving a large amount of computing in the aggregate. Furthermore, the lack of sharpness of the flocculi (as compared with spots), and their rapid changes of form, rarely permit of the precision of setting attainable in the case of spots, and render a different mode of measurement feasible. It will appear, however, that in its perfected form the instrument described in this paper is capable of giving results no less precise than the ordinary measuring machine.

The first and simplest form of the instrument, which I devised for the measurement of the Kenwood spectroheliograph plates by Mr. Fox at the Yerkes Observatory, consists of a metallic globe, with smooth white surface, upon which the solar image is optically projected. The axis of the globe being set at the inclination required by the date of the photograph, and the plate properly oriented, it is only necessary to read off the heliographic latitudes of the flocculi and their differences in longitude from the sun's center, by the aid of parallels and meridians ruled, one degree apart, on the surface of the globe. The results obtained with this simple device were so satisfactory that it is still regularly employed in the measurement of the Rumford spectroheliograph plates. The essential condition to be met is that the angular diameter of the globe, as seen from the projecting lens, shall equal the angular diameter of the sun, as seen from the earth.[1]

In the second form of the instrument, as constructed in the shops of the Solar Observatory, two 4-inch (10 cm) telescopes were mounted parallel to one another. One of these pointed at a globe, 60 feet (18.29 m) distant, beside which stood the solar photograph to be

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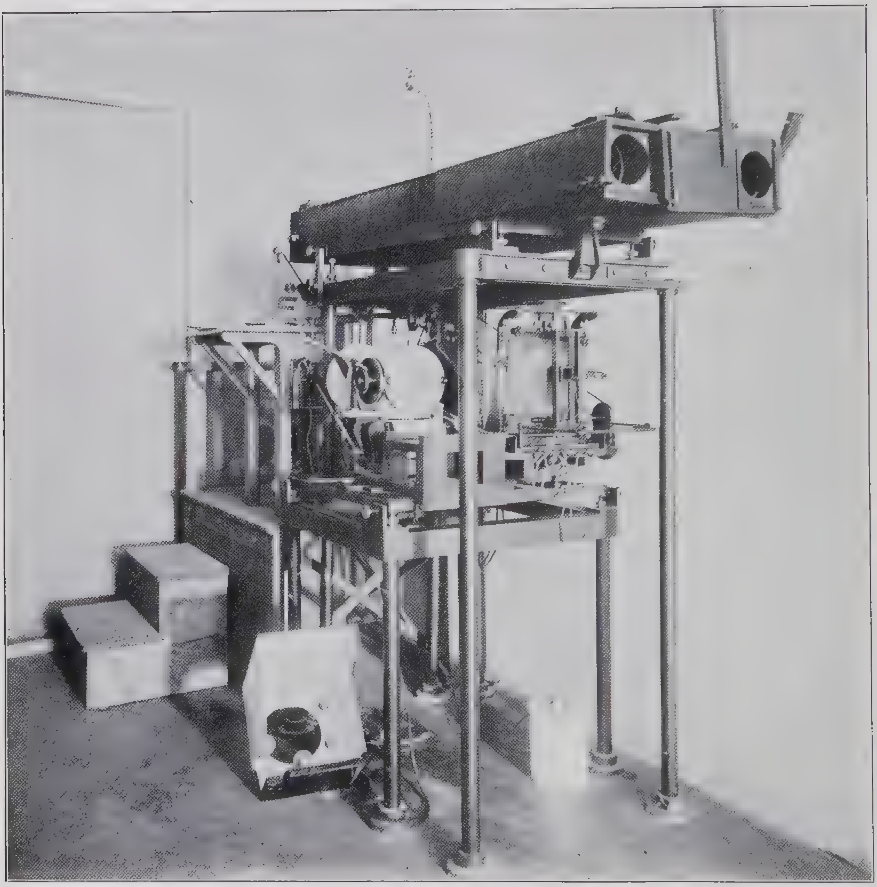
[1] A full description of this instrument will soon appear in a paper by Mr. Fox and myself on the solar rotation.

PLATE XVIII



The Heliomicrometer

measured, with its center in the optical axis of the other telescope. The images of globe and plate, as formed by the two telescopes, were brought together in a single eyepiece, by means of a half-silvered prism. After the photograph had been oriented and centered on the globe, by adjustments controlled from the observer's seat, the latitudes and longitudes of the flocculi were read off with respect to parallels and meridians, ruled one degree apart, on the surface of the globe. This instrument gave good results, but the illuminated surface of the globe (black lines on a matt silvered surface) interfered with the visibility of the minute flocculi. Experiments with cross-hairs for setting purposes, and the desire to secure a higher degree of precision than estimates to a tenth of a degree could afford, soon led me, by successive steps, to the design embodied in the "heliomicrometer," which is illustrated in Plate XVIII.

The two 4-inch telescopes, of 60 inches focal length, which were used in the second form of the instrument described above, are retained and mounted immediately above the globe and the plate-carrier. These telescopes point to the centers of two optically plane mirrors, mounted on a concrete pier at a distance of about 30 feet (9.14 m). In the telescope on the right, the solar image, brilliantly illuminated by transmitted light, is seen after reflection from one of the plane mirrors. In the same way the globe, illuminated by reflected light, may be seen in the telescope on the left. The images are brought together in a single eyepiece, with the aid of a right-angle prism at the end of each telescope and a half-silvered prism, similar to that used in the monocular eyepiece of Zeiss's stereocomparator, mounted a short distance in front of the eyepiece.

As a complete description of the apparatus will be published later, only its general features are described in the present paper. The adjustments of the plate-carrier permit the photograph to be raised or lowered, moved right or left, rotated for orientation, and moved toward or from the mirror. Cross-hairs, mounted immediately in front of the plate,[1] are controlled from the eyepiece, and their intersection can be made to coincide with the flocculus to be measured. While settings are thus being made, the object-glass of the telescope which points to the globe is covered by a swinging shutter, controlled by the observer. Under these conditions the details of the solar photograph are seen with great clearness, and settings are made as easily and rapidly as in any form of measuring machine.

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[1] The same support carries the electric pen, referred to below.

The entire globe has a matt silvered surface, and one hemisphere shows no lines except the equator and central meridian. These lines do not quite reach the center of the globe. At the point where they would intersect, a small circular black dot is engraved. This is brought into coincidence with the intersection of the cross-hairs, by rotating the globe in longitude and latitude. In longitude the globe has both quick and slow motions, permitting a rapid and accurate setting to be made. In latitude a single motion, consisting of a worm-gear operated by an arm with double Hooke's joint, gives sufficiently rapid motion, combined with perfect control. The longitude circle, provided with a vernier reading to tenths of a degree, or, if desired, to 2′, is read with a telescope from the eye-end. The globe is then turned back to zero longitude, and at this point the latitude circle, also reading to tenths of a degree or to 2′, is read with a second telescope.

The vertical axis that carries the fork in the opposite bearings of which the horizontal axis of the globe rests, can be set at any desired angle, read by means of a vernier and divided circle. The inclination of this axis corresponds to the tabulated latitude of the center of the sun for the date of the photograph.

It is unnecessary to give here the details of the adjustments of the apparatus. It may be added, however, that the photographs made with the Snow telescope and 5-foot spectroheliograph are oriented by the aid of control plates, on which the solar image is allowed to drift between two exposures. A line joining two images of the same flocculus gives the east and west direction. The angle between this line and a line drawn on the plate by the image of a needle-point mounted in contact with the collimator slit provides the means of orientation. The centering of the solar image on the globe is easily effected, with the aid of a metallic screen mounted in front of the globe and bearing a black circle, adjusted so as to be exactly concentric with the globe. This circle should coincide, when the instrument is in adjustment, with a black circle etched in a glass plate permanently fixed in the adjustable plate-carrier. This circle is slightly larger in diameter than the solar photograph which can thus be centered with great precision. In order to provide for the varying size of the image, due to the varying distance of the sun from the earth, the plate-carrier can be moved along rails, so as to change its distance from the telescope with which it is observed. The necessary adjustment of focus is made by moving the object-glass of the corresponding telescope.

Measurements are confined to objects within fifty degrees of the sun's center. This is for the purpose of avoiding errors inevitable when spots or flocculi are measured in the near neighborhood of the sun's limb. Furthermore, it is not necessary, within this limited region, to change the focus of the telescope used to observe the globe.

In testing the heliomicrometer, a photograph of the sun was measured with this instrument and with an ordinary measuring machine, giving polar co-ordinates. After the reductions had been completed, it was found that the latitudes and longitudes of the flocculi, measured in the two ways, agreed within the limits of error of settings (one or two tenths of a degree). The operations of measurement proved as rapid with the heliomicrometer as with the other measuring machine, and all the time required for calculations was saved. A further test was made by measuring the positions of certain sun-spots, which also appear on the Greenwich photographs. Mr. Maunder was kind enough to give me the positions of these spots as determined at Greenwich. The results correspond within a few tenths of a degree, or as closely as could be expected under the circumstances.[1]

It should be stated here that Dr. Frank Schlesinger, with whom I had the benefit of discussing the first globe measuring instrument used at the Yerkes Observatory, suggested, in 1902, that an ordinary theodolite, provided with a small pointer in place of the telescope, might give good results in this work. The details of the apparatus were not worked out, and I had forgotten the suggestion, when I was led by the above described steps to the adoption of the same principle, namely, the use of divided circles in place of meridians and parallels ruled on a globe. This important element in the design is therefore due to Dr. Schlesinger. It is evident that a globe is not really required (as a pointer might suffice), but it has the advantage of permitting one surface to be divided into ten-degree squares, used as described below.

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[1] The centers of spots on spectroheliograph plates are often slightly displaced by overhanging flocculi.

My attention has been called, by Professor A. E. Douglass, to his paper published in *Popular Astronomy* (No. 42, 1897), entitled "The Astronomer's Globe." This globe was used for the solution of spherical triangles. The positions of markings on *Mars* were also plotted on the surface of the globe, and their latitudes and longitudes read off with the aid of two divided semi-circles, which could be moved over the surface. The same, of course, could be done with sun-spots. I do not understand that any system of optical projection was used with this globe.

It will be readily seen that the heliomicrometer can be used as a stereocomparator (with monocular or binocular vision). For this purpose it is only necessary to mount in front of the globe a second photograph, illuminated by transmitted light. Miss Ware, who is in charge of the heliomicrometer, uses this arrangement for comparing the forms of the flocculi photographed on successive days, in order to select points suitable for measurement. By means of an electric pen, controlled from the eyepiece, a small dot is made on the glass side of the plate, for purposes of identification, near each point selected.

One hemisphere of the globe is ruled with meridians and parallels ten degrees apart. When seen in projection on the globe (the axis of which is given the proper inclination for the date in question), the intersections of the squares can be marked on the glass side of the plate by means of the electric pen. Plates marked in this way are used by Miss Smith in her photometric measures of the areas of the calcium flocculi within ten-degree regions. The data thus secured are employed in our studies on the variation of the solar activity, with reference to the condition of the sun as a whole, and its activity in different zones of latitude and longitude.

The heliomicrometer could be improved by supporting all parts of the apparatus shown in Plate XVIII on a stone or concrete pier. The present instrument, which is fastened to a concrete floor and braced to an adjoining brick wall, gives very satisfactory results, but is less stable than if it had been designed anew, instead of being modified from the second form of the instrument, described above. I am indebted to Mr. Pease for working out the detailed drawings.

In view of the rapidity of measurement, and the accuracy of the results obtained with this instrument, I can recommend it for the determination of the heliographic positions of spots and flocculi shown on direct photographs or on spectroheliograph plates.

April 1907

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 17

Preprinted from the *Astrophysical Journal*, Vol. XXV (June), 1907

A PHOTOGRAPHIC COMPARISON OF THE SPECTRA OF THE LIMB AND THE CENTER OF THE SUN

By GEORGE E. HALE and WALTER S. ADAMS

Prior to 1873, although the spectra of the limb and the center of the sun were compared by several observers, no differences in the relative intensities of the Fraunhofer lines were detected. In that year Hastings[1] noticed that some of the lines changed their appearance at the limb. In 1879 and 1880 he continued the investigation with improved apparatus. The results of the later observations, which were made visually with a Rutherfurd grating spectroscope, are given by Hastings as follows:

> I. The most important fact of all is that the differences in the two spectra of center and limb are extremely minute, escaping all but the most perfect instruments, and all methods which do not place them in close juxtaposition.
>
> II. Certain lines, the thickest and darkest in the spectrum, notably those of hydrogen, magnesium, and sodium, which appear with haze on either side, in the spectrum of the center of the solar disk, are deprived of this accompaniment in that of the limb.
>
> III. Certain very fine lines (four observed) are stronger at limb.
>
> IV. Other very fine lines (two or three observed) are stronger at center.[2]

Hastings, referring to the spectrum of sun-spots, remarks:

> As is well known, such a spectrum exhibits a very strong general absorption, with a very slightly modified selective absorption. A few faint lines appear in the spot spectrum which are not otherwise seen; and a few faint lines of the ordinary spectrum are strengthened. A careful examination has persuaded me that the spectrum of a spot differs from that of the unbroken photosphere, just as the spectrum of the limb differs from that of the center of the disk, save that the variations are more pronounced.

In spite of the great interest and importance of these observations, they do not appear to have been repeated in the long interval which has elapsed since Hastings made them. A photograph by Jewell, reproduced in Young's *Manual of Astronomy*, page 221, shows that the H_1 and K_1 bands are greatly weakened at the limb, and this effect seems to have been recognized by Deslandres in some of his papers, but we have seen no discussion of any other important changes from center to limb. In her *Problems in Astrophysics* (p. 42), the late Miss Clerke, after discussing various details of the Fraunhofer lines, writes as follows: "An embarrassing peculiarity of the Fraunhofer lines is their virtually uniform existence all over the sun's disk."

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[1] *American Journal of Science*, **5**, 369–371, 1873.

[2] *Ibid.*, Third Series, **21**, p. 35, 1881.

Our first photographic comparisons of the spectra of the limb and the center of the sun were made in the red region of the spectrum, mainly for the purpose of testing Halm's recent results regarding line displacements.[1] It was noticed at once that many of the lines on the plates showed slight changes of relative intensity, which promised to be of interest in connection with our sun-spot investigations. As the discussion in our last paper[2] indicates, we have been occupied with the problem of distinguishing between the changes in the appearance of lines produced by differences in temperature and by differences in the density of the vapors. In this connection, we had long since planned to take up an investigation of the spectrum of the limb as compared with the center of the sun. It was supposed, however, that the differences would be so slight that they could be detected only with difficulty, and a special means of testing suspected cases, by a photometric study of spectroheliograph plates made for this particular purpose, was devised. It will be seen from the results contained in the present paper that the differences, particularly in the more refrangible part of the spectrum, are so striking that no such device is required.

The photographs hitherto taken cover almost the entire length of the spectrum from λ 3600 to λ 7000. They were made with the Snow telescope and the Littrow spectrograph described in our previous papers on sun-spot spectra. The image of the sun on the slit has a diameter of about 6.7 inches (17.02 cm). The spectrograph is of 18 feet focal length and contains a 4-inch Rowland grating, having 14,438 lines to the inch (5700 lines to the cm). Most of the spectra were photographed in the third order, but some were taken in the

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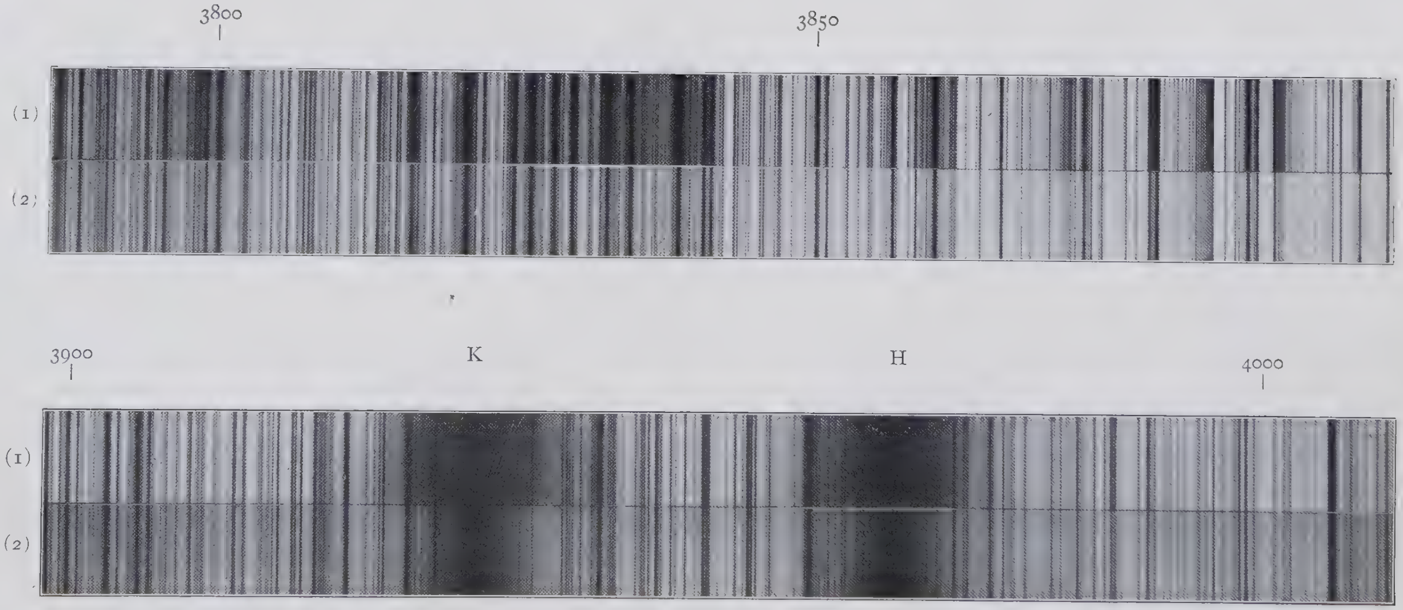
[1] *Astronomische Nachrichten*, No. 4146–47, 1907.

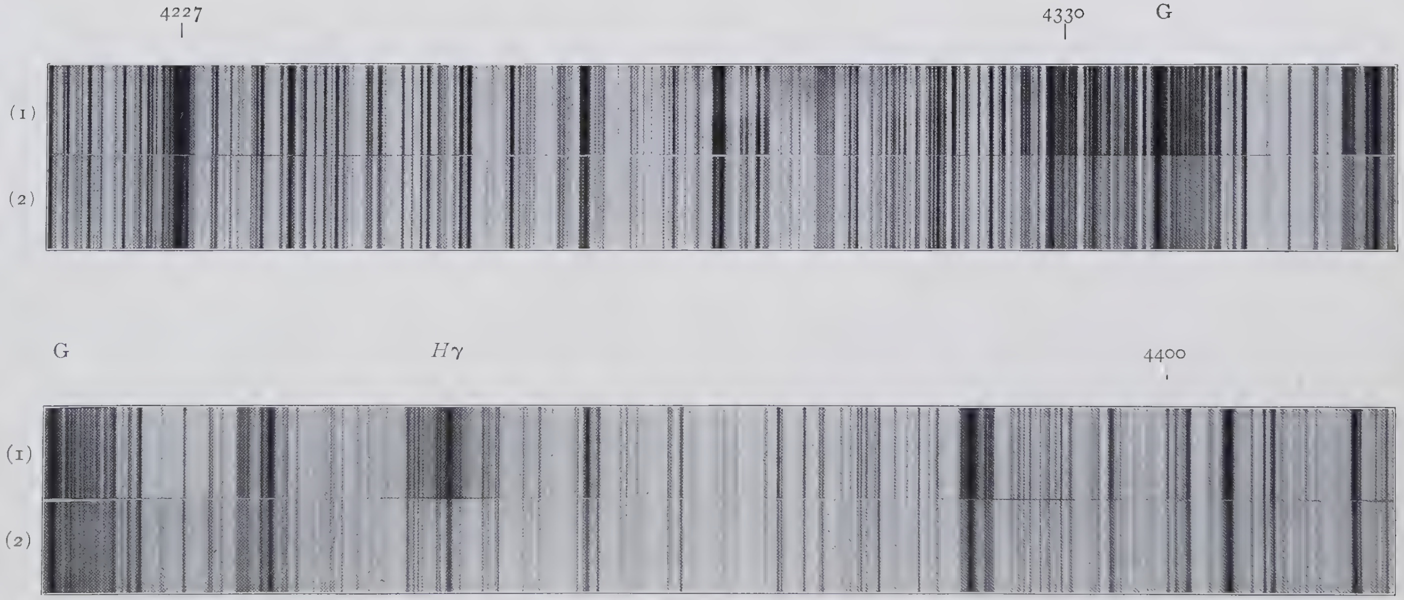
[2] *Contributions from the Solar Observatory*, No. 15.

PLATE XIX



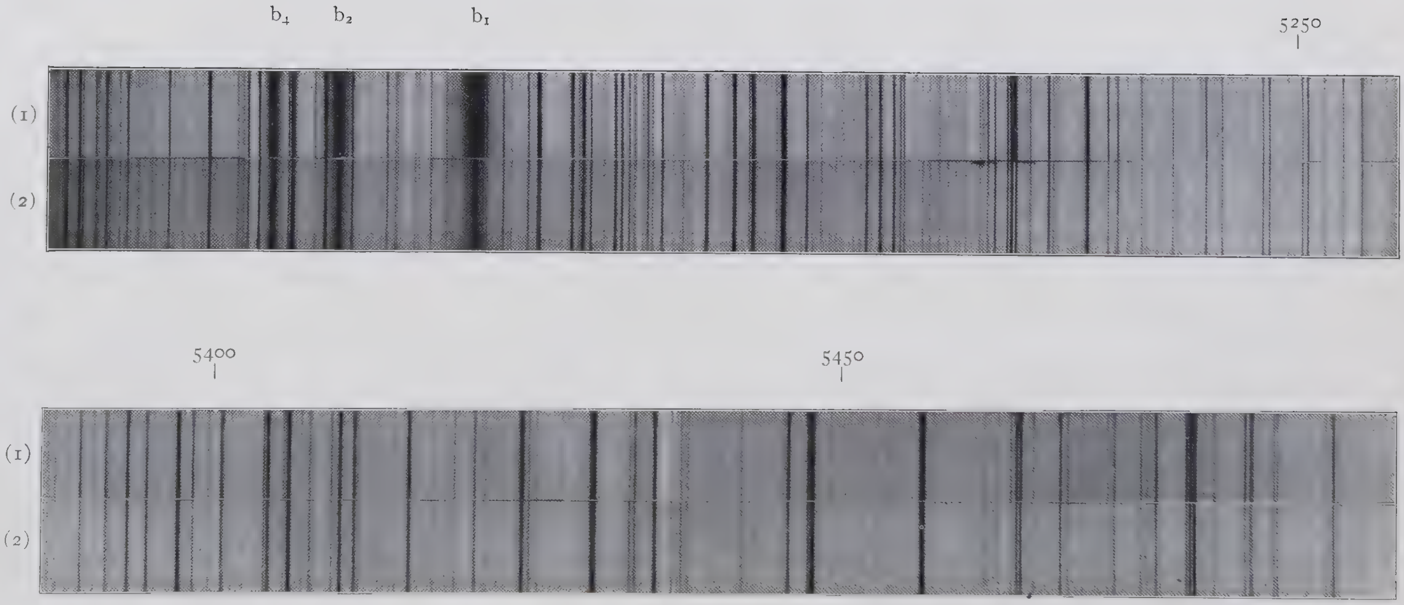
Spectra of (1) Center of Sun, (2) Limb

PLATE XX



Spectra of (1) Center of Sun, (2) Limb

PLATE XXI



Spectra of (1) Center of Sun, (2) Limb

second, and a few in the fourth, the last for the study of line displacements. In making the exposures the image of the sun was adjusted so that the slit was parallel to a tangent at the limb, and usually about one millimeter within it. Precautions were always taken to prevent any light from the chromosphere from entering the slit. Hence, in all cases, the photographs of the spectrum of the limb represent the sun's disk, and not the region lying outside of it. After the exposure for the limb had been completed, a small sliding bar was moved over the slit, so as to cover the portion previously exposed, and light from the center of the sun was admitted on each side of the bar. Thus each photograph of the spectrum of the limb lies between two strips of spectrum representing the center of the sun. In the violet it is necessary to give from eight to ten times as much exposure at the limb as at the center. This ratio is reduced to four or five at the red end of the spectrum.

As an examination of Plates XIX, XX, and XXI will indicate, the differences in the relative intensities of the lines are not very marked in the less refrangible region, except in the case of such winged lines as D_1 and D_2, b_1, b_2, and b_4. In these cases the wings are greatly reduced in intensity, and the central portions of the lines are strengthened in the spectrum of the limb—a result which is in complete agreement with the observations of Hastings. There are some very distinct differences of line intensity to be noticed in this region, but such effects become far more marked in the blue and violet, and very conspicuous in the ultra-violet. In the region λ 3815–λ 3840 the appearance of the spectrum is greatly changed, through the almost complete disappearance of the wings which characterize the stronger lines corresponding to the center of the disk. So far as we have yet observed, in our preliminary examination of the plates, this practical elimination of the wings applies to all lines of this character. It is therefore to be regarded as the most striking feature of the spectrum of the sun's disk near the limb. In spots, on the other hand, a marked strengthening of the wings is a well-known characteristic in the less refrangible region of the spectrum. If this applies in the same degree to the much more closely crowded lines of the ultra-violet, it may be one of the causes contributing to the extreme weakness of the spot spectrum in this region.

A second important distinction between the spectrum of the limb and the center lies in the changes in the relative intensities of the lines. In general, as the brief tables based upon a preliminary examination of several regions indicate, these changes of line intensity correspond closely with those observed in the case of sun-spots. In other words, lines that are strengthened in sun-spots are usually strengthened, in much smaller degree, near the sun's limb. Furthermore, lines which are weakened in sun-spots are usually weakened at the limb. Indeed, this latter effect seems to be relatively more marked than the effect of strengthening throughout the whole range of the spectrum. Some important exceptions have been noted, and others will no doubt appear in a more complete examination of the photographs. Nevertheless, the resemblance in this particular of the spectrum of the limb to that of sun-spots is very marked, especially in the less refrangible region. In the violet and ultra-violet the resemblance is partially concealed by the presence, in the case of spots, of an overlying solar spectrum. It is, however, clearly indicated. In our last paper we discussed the two principal sources to which this solar spectrum could be ascribed, namely, photospheric light and general sky illumination. Our present results on the spectrum of the center and the limb indicate that the photospheric light must probably be much the more important—a conclusion which agrees with that of Newall.[1]

In the tables which follow we give the results of our comparison of the spectrum of the center with that of the limb for three regions in different parts of the spectrum. The first of these includes a part of the G group and $H\gamma$; the second, the b lines and a portion of the green; and the third, a region in the yellow which is of considerable interest in sun-spot spectra. These results are merely preliminary and are given mainly to indicate the character of the evidence connecting changes in line intensities at the limb with those in spot spectra. In the abbreviations "Str." indicates that the line is strengthened, and "Str.+" that the effect is marked. Similarly "Wk." indicates that the line is weakened, and "Wk.+" that the amount of weakening is considerable. Lines in which the wings are reduced are indicated by "Sharp.," an abbreviation for sharpened.

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[1] *Monthly Notices,* January 1907.

TABLE I

λ	Element	Intensity Rowland	Spot	Limb
4299.15	*Ca*	3	Str.	Str.+
99.41	*Ti, Fe*	4		Sharp.
99.80	*Ti*	2	Str.	Wk.?
4300.21	*Ti*	3	Wk.?	N. C.
00.48	—	1 N		Wk.+
00.73	*Ti*	2	Str.	Wk.?
00.99	—	1	Wk.?	Wk.
01.16	*Ti*	2	N. C.	Wk.+
.26	—	4		
.33	—	1		
02.35	*Fe*	2		Wk.+
02.46	—	2		Wk.+
02.69	*Ca*	4	Str.+	Str.+
03.34	*Fe*	2	Wk.	Wk.+
03.75	—	1	N. C.	Wk.?
03.99	—	2	Wk.	Wk.+
04.10	—	4		
04.73	—	2	Wk.	Wk.+
05.27	—	1	Wk.?	Wk.+
05.48	*Fe, Sr*	1	Wk.	Wk.?
05.61	*Ti, Cr*	3		
05.87	—	2		N. C.
06.08	*Ti*	4	Str.	Wk.?
06.30	—	2	N. C.	Wk.+
06.86	—	–	Wk.	Wk.+
07.02	—	2		
07.46	—	2 N		Wk.+
07.72	—	2 Nd?		Wk.+
07.91	*Ca*	3	Str.	Str.+
08.08	*Fe, Ti*	6		Str.?
08.76	—	2 Nd?		Wk.++
09.06	—	1	Wk.	Wk.+
09.20	*Fe*	2		
09.54	*Fe*	3	Str.?	N. C.
09.79	—	1	Wk.	Wk.+
.88	—	1		
10.27	—	2	Wk.	Wk.+
10.54	—	1	Wk.	Wk.+
.63	—	2		
10.86	—	2	N. C.	Wk.+
11.06	—	1	Wk.	Wk.+
.15	—	1		
11.32	—	2	N. C.	Wk.+
11.61	—	2	Wk.+	Wk.+
.67	—	2		
12.25	—	2		Wk.+
12.46	—	2		Wk.
12.72	*Mn*	1 N		Wk.?
13.03	*Ti*	3	Wk.?	Wk.
13.19	—	1 N		Wk.
14.25	*Sc*	3	Str.	Str.+
15.14	*Ti*	3	Str.	N. C.
.26	*Fe*	4		Str.
16.96	*Ti?*	1	Wk.?	N. C.

TABLE I—*Continued*

λ	Element	Intensity Rowland	Spot	Limb
4318.82	*Ca, Mn?*	4	Str.+	Str.+
20.91	*Sc*	3	Str. ?	Str. ?
21.12	*Ti?*	2	Wk. ?	Str. ?
21.96	*Fe*	2	Str. ?	Wk. ?
23.39	—	2	Wk.	Wk.+
23.67	—	1		Wk.+
23.77	—	0		Wk.+
24.01	—	3	Wk.	Wk.+
24.57	—	2	Wk. ?	Wk.
25.15	*Sc*	4	Str.	N. C.
25.31	*Ti, Cr*	1		
25.52	*Ni, Zr*	1		Wk.+
25.94	*Fe*	8		Sharp.+
26.52	*Ti*	0	Str.+	Str.
26.92	*Fe*	2	Str. ?	Str. ?
28.08	*Fe*	2	Str. ?	Wk.
30.19	*Fe*	0	Str.+	N. C.
30.40	—	1	Wk.	Wk.
30.87	*Ti, Ni*	2	Wk.	Wk.+
31.81	*Ni*	2	Str.	Str.+
32.99	*V*	0	Str.+	Str. ?
33.92	*La*	1		Wk.+
35.10	*La*	0	Str.	N. C.
37.22	*Fe*	5	Str.	N. C.
37.72	*Cr*	3	Str.	Str.
38.08	*Ti*	4	Wk.	N. C.
38.43	*Fe*	1	Str.+	Str.
39.62	*Cr*	4	Str.+	Str.
39.88	*Cr*	3	Str.	Str.+
40.63	*H*	20	Wk.+	Wk.+Sharp.!
41.17	*V*	0	Str.+	Str.
41.53	*Ti?*	2	Wk.	N. C.
43.37	*Cr*	2	N. C.	N. C.
43.43	*Fe*	2		
44.67	*Cr*	4	Str.+	Str.+
46.99	*Cr*	1	Str. ?	Wk. ?
47.40	*Fe*	1	Str.+	Str.+
51.00	*Ti*	1	Wk. ?	Wk.
51.22	*Cr*	3	Str.+	Str.+
51.93	*Cr, Fe*	5	Str. ?	Wk.
52.08	*Mg*	5		N. C.
52.91	*Fe*	4	Str.+	Str.+
53.04	*V*	0		
55.26	*Ca?*	2	Str.	Wk.+
5137.25	*Ni*	3	Str.+	Str.+
39.43	*Fe*	4	Str.+	Str.
39.64	*Fe*	4	Str. ?	Str. ?
40.99	—	00	Wk.	Wk.
41.92	*Fe*	3	Str.+	Str.+
42.96	*Ni*	2	Wk. ?	Wk. ?
43.11	*Fe*	3	Str.	Str.
43.76	—	000	Str.+	Str.+
43.90	—	00		
44.85	*Cr, C*	00	Str.+	Str.

TABLE I—*Continued*

λ	Element	Intensity Rowland	Spot	Limb
5145.27	*Fe*	1	Str.+	Str.+
45.64	*Ti*	0	Str.	Str.
46.66	*Ni*	3	N. C.	Str. ? Wid.
47.65	*Ti*	0	Str.+	Str.+
48.22	*Fe*	2	Wk.	N. C.
48.41	*Fe*	3	Str. ?	Wk.+
51.02	*Fe*	4	Str.+	Str.+
52.09	*Fe*	3	Str.+	Str.+
52.36	*Ti*	0	Str.+	Str.+
53.41	*Fe*	1	Str.	Wk.+
53.58	—	00		
53.69	—	00		
54.24	*Co*	2	Wk.	N. C.
55.94	*Ni*	2	Str.	Wk.
56.78	*C*	000	Str.	Str. ?
56.82	*C*	00		
59.23	*Fe*	2	Wk.	N. C.
62.45	*Fe, C*	5	Wk. ?	Wk.+Sharp.
64.72	*Fe ?*	1	Wk.	Wk.
65.59	*Fe*	2	N. C.	Str ?
66.45	*Cr, Fe*	3	Str.	Str.+
67.50	*Mg*	15	Str.+	Str.+Sharp.!!
67.68	*Fe*	5		
69.07	*Fe*	3	Str.	Str.+
69.22	*Fe*	4	Wk.+	Wk.
70.94	*Fe*	0	Wk.+	Wk.+
71.78	*Fe*	6	Str.	Str. ?
72.86	*Mg*	20	Str.+	Str.+Sharp.!!
73.92	*Ti*	2	Str.	Str.+
76.30	—	000	Str.	Str.
76.73	*Ni*	1	Wk.	Wk.
77.41	*Fe*	0	Str. ?	Str. ?
77.58	*Co*	00		Str. ?
80.23	*Fe*	1	Str. ?	Str. ?
83.79	*Mg*	30	Str. ?	Str.+Sharp.!!
84.44	*Fe*	2	Wk. ?	Wk.+
84.74	*Fe, Ni, Cr*	1	Wk.	Wk.+
86.07	*Ti*	2	Wk.+	Wk. ?
88.08	*Fe*	1	Wk.	N. C. Wid.
88.86	*Ti*	2	Wk.	Wk.
89.02	*Ca*	3	Str.+	N. C.
91.63	*Fe*	4	Str. ?	Str. Sharp.
92.52	*Fe*	5	Str.	Str. Sharp.
93.14	*Ti*	2	Str.+	Str.+
95.11	*Fe*	4	Str.+	Str.+
95.65	*Fe*	2	N. C.	Str. ?
96.23	*Fe*	1	Str.	Str.
96.61	*Cr*	0	Str.	Str.
96.74	*Mn*	00		Str.
97.33	*Ni, Mn*	00	Wk.	N. C.
97.74	—	2	Wk.+	Wk.+
98.89	*Fe*	3	Str.+	Str.+
5200.59	*V*	0	Str. ?	Str.

TABLE I—*Continued*

λ	Element	Intensity Rowland	Spot	Limb
5202.44	*Fe?*	2	N. C.	N. C.
02.52	*Fe*	4		
04.68	*Cr*	5	Str.+	Str.
04.76	*Fe*	3		
05.90	*Y*	0	Wk. ?	Wk. ?
06.22	*Cr–Ti*	5	Str.+	Str.+
08.11	*Ti*	00	Str. ?	N. C.
08.60	*Cr*	5	Str.+	Str.+
08.78	*Fe*	2		Wk. ?
10.56	*Ti*	3	Str.+	Str.+
11.70	*Fe*	00	Wk.	N. C.
16.44	*Fe*	3	Str.+	Str.+
17.55	*Fe*	3	Str. ?	Str.
18.37	*Fe*	1	Wk.	Wk.
19.88	*Ti*	0	Str.+	Str.+
20.36	*Ni*	0	Wk.	N. C.
22.56	*Cr*	00	Str.	Str.
23.35	*Fe*	0	N. C.	Str. ?
24.47	*Ti*	0	Str.	N. C.
25.10	*Cr*	0	Str.	Wk.
25.20	*Cr, Ti, Fe*	00		N. C.
25.70	*Fe*	2	Str.+	Str.+
26.71	*Ti*	2	Wk. Wid.	N. C. Wid.
27.04	*Fe–Cr*	3	Str.	Str.
27.36	*Fe*	5 D?	Str.+	Str. Sharp.
30.03	*Fe*	4	Wk. ?	N. C.
30.38	*Co, Cr*	00	Str.	Str. ?
33.12	*Fe*	7	Str.+	Str. Sharp.!
34.79	—	2	Wk.+	Wk.+
35.56	*Fe*	1	Wk.	Wk. ?
35.67	*Ni*	00		
36.37	—	0	Wk.	Wk.
37.49	*Cr?*	1	Wk.	Wk.
38.74	*Ti*	000	Str.+	Str.+
39.14	*Cr*	00	Str.	Str.
39.99	—	1	Wk.	N. C.
42.66	*Fe*	2	Str. ?	N. C.
43.95	*Fe*	1	N. C.	N. C.
47.23	*Fe*	1	Str.+	Str.+
47.74	*Cr*	2	Str.+	Str.+
5397.34	*Fe*	7 d?	Str.+	Str. Sharp.
98.49	*Fe*	3	Wk. ?	N. C.
99.68	*Mn*	1 Nd?	Str. ?	N. C.
5400.71	*Fe*	3	Wk. ?	Wk.+
00.83	*Cr*	00		
04.03	*Fe*	2	Wk. ?	N. C.
04.36	*Fe*	5	N. C.	Wk. ? Sharp.
05.99	*Fe*	6	Str.+	Str. Sharp.
07.59	*Mn*	0	Str.	Str.
07.69		0		
07.82	—	00	Wk.+	Wk.
09.34	*Fe*	2	Wk.+	Wk.
10.00	*Cr*	4	Str.+	Str.+
11.12	*Fe*	4	Wk. ?	Wk.

TABLE I—*Continued*

λ	Element	Intensity Rowland	Spot	Limb
5411.43	*Ni*	1	Wk.+	Wk.
14.28	—	00	Wk.	Wk.
15.42	*Fe–V*	5	N. C.	N. C. Sharp.
18.98	*Ti?*	1	Wk.?	N. C. Wid.
20.55	*Mn*	0	Str.+	Str.+
20.61		0		
24.29	*Fe*	6	N. C.	N. C. Sharp.
24.86	*Ni*	1	Str.?	Str.
25.46	—	1	Wk.	Wk.
26.47	—	00	Str.+	Str.
29.72	—	1	Wk.?	Wk.+
29.91	*Fe*	6 d?	Str.+	Str.+ Sharp.
32.75	*Mn*	1 Nd?	Str.+	Str.+
34.74	*Fe*	5	Str.+	Str.+ Sharp.
36.07	*Ni*	2	Str.?	Str.
36.51	*Fe*	1	Wk.?	N. C.
36.80	*Fe*	1	Str.+	Str.
41.55	*Fe?*	1	Wk.?	N. C.
45.26	*Fe*	4	Wk.?	N. C.
46.80	*Ti*	2	Str.+	Wk.?
47.13	*Fe*	6 d?	Str.+	Str. Sharp.
55.67	*Fe?*	2	Str.	Wk.
55.83	*Fe*	4		Str.
60.72	—	00	Str.+	Str.
61.76	—	0	Str.	N. C.
63.17	*Fe*	3	Wk.?	Wk.?
66.61	*Fe*	3	Str.	Str.?
67.20	*Fe*	1	Str.?	Str.?
70.80	*Mn*	0	Str.+	Str.
70.88		0		
72.92	*Fe*	1	Str.	Str.
74.11	*Fe*	3	Wk.	Wk.
76.50	*Fe*	1	Wk.?	Wk.+
77.12	*Ni*	5	Str.+	Str.? Wid.
77.90	*Ti*	00	Str.+	N. C.
78.67	*Fe*	0	Wk.	Wk.
81.45	*Fe*	1	N. C.	Wk.
81.65	*Fe, Ti*	1	Str.	Wk.?
82.08	—	00	Str.+	Str.
83.31	*Fe*	1	Wk.	Wk.
83.57	*Co*	1 d?	Str.+	Str.+
90.37	*Ti*	0	Str.+	Str.+
93.71	*Fe*	1	Str.	Str.?
97.74	*Fe*	5	Str.+	Str. Sharp.

The tendency toward a weakening of the spark lines, which is unmistakable though not very marked in the less refrangible region of the spectrum, becomes conspicuous in the violet and ultra-violet. The following list, taken from Lockyer's "Tables of the Wave-Length of Enhanced Lines," indicates the behavior in this respect of the more prominent spark lines of *Fe*, *Ti*, and *V* in the ultra-violet region. Identifications not made by Rowland are entered in brackets.

TABLE II

λ	Element	Intensity Rowland	Spot	Limb
3685.34	*Ti*	10 d?	Wk.	Wk.++
3706.36	*Ti*	3		Wk.+
3721.78	*Ti*	4 d?	Wk.	Wk.++
3741.79	*Ti*	4	Wk.	Wk.++
3748.14	*Ti*	1		Wk.++
3757.82	*Cr–Ti*	4	Wk.?	Wk.++
3759.45	*Ti*	12 d?	Wk.+	Wk.++Sharp.!
3761.46	*Ti*	7	Wk.+	Wk.++
3762.01	*Ti*	3		Wk.+
3776.20	*Ti*	2		Wk.+
3813.54	*C (Ti)*	2		Wk.+
3814.74	*–C (Ti)*	3		Wk.+
3836.23	*(Ti)*	2		Wk.
3839.76	*Fe*	2	Wk.	Wk.++
3846.55	*Fe*	2		Wk.++
3863.89	*Fe*	3	Wk.	Wk.++Sharp.
3866.96	*C–(V)*	2	Wk.?	Wk.+
3878.88	*C–Fe (V)*	2	Wk.?	Wk.++
3900.68	*Ti–Fe–Cr*	5		Wk.++
3903.40	*(V)*	2	Wk.	Wk.++
3913.61	*Ti–Fe*	5 d?	Wk.	Wk.
3914.43	*Fe? (V)*	3		Wk.++
3916.54	*(V)*	3	Wk.?	Wk.+
3935.96	*Fe*	2		Wk.
3939.29	*(Fe)*	0		Wk.+
3987.76	*Ti?*	2	Wk.?	N. C.
4005.86	*(V)*	3		Wk.+
4012.54	*Ti*	4		Wk.

In considering the behavior of the lines of different elements, we encounter at once an interesting peculiarity, which may prove significant. In the spot spectrum the lines of titanium and vanadium are well known to be very conspicuous, because, in most cases, they are strengthened more than the lines of other substances. In the spectrum of the limb, however, while these lines seem to be affected in the same direction as in spots, the magnitude of the effect is decidedly less than in the case of manganese, iron, calcium, and other substances, which appear to behave more nearly as they do in spots.

Hydrogen offers another case of great interest, with one apparent anomaly. $H\beta$ is not satisfactorily shown on the photographs at present available, and may for the present be left out of consideration. $H\gamma$ and $H\delta$ are much sharper and narrower at the limb than at the center of the sun, largely through the weakening of the wings which accompany these lines. The central part of the lines also appears to be slightly weakened at the limb. In spots they act in the same way, but the effect is more marked. *Hα* is certainly widened at the limb and possibly somewhat strengthened. There appears to be no great change in the sharpness of the line, the edges being slightly diffuse in both cases. In spots, on the contrary, *Hα* is much narrower than in the spectrum of the sun's center and is also weakened. We have as yet found no means of explaining this apparent anomaly.

Carbon and cyanogen are particularly interesting. Many lines in the violet carbon band are of unchanged intensity, or perhaps slightly strengthened, at the limb. The cyanogen fluting, which begins at λ 3884, is, on the contrary, very decidedly weakened at the limb. This is clearly shown in Plate XIX.

The behavior of the spark lines is a matter of special interest. In addition to the lines given in the list, the very noticeable weakening of most of the lines of the G group may be mentioned. The great majority of these are unidentified by Rowland, and are probably spark lines. The more conspicuous of these lines are weakened in spots, and doubtless others would be were they not concealed, as suggested in our last paper,[1] by the overlying solar spectrum.

The behavior of the line λ 4233.3, which is probably mainly due to enhanced *Fe*, as shown by Lockyer, is of special interest, as this line is very strong in the flash spectrum. At the limb, on the contrary, it is much weakened. There are doubtless many other cases of this kind which will require careful investigation.

The bearing of these results on solar theory cannot properly be discussed until much more material is available, particularly as regards relative intensities and line shifts. These investigations are now in progress, and we therefore reserve further discussion for a later paper, in spite of various seemingly obvious consequences which at once suggest themselves. For example, it now seems difficult to reconcile our results as to the disappearance of wings at the limb with Halm's conclusion that the dense vapors lying close to the photosphere contribute relatively more at the limb than at the center to the formation of the absorption lines. We hope at an early date to be able to discuss this point fully, as well as many more of equal interest.

April 1907

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[1] *Contributions from the Solar Observatory*, No. 15.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 18

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SOME NEW APPLICATIONS OF THE SPECTROHELIOGRAPH

By GEORGE E. HALE

I. SOLAR PHOTOGRAPHY WITH SUN-SPOT LINES

In several previous papers I have remarked on the importance of photographing the sun with the lines affected in and near spots. In our photographs of spot spectra many lines are strengthened or weakened, not merely in the umbra and penumbra, but in extensive regions surrounding spots. This effect, conspicuous enough to show itself directly in the spectrum, is evidently within easy reach of the spectroheliograph. Furthermore, our experience in the photography of faint hydrogen flocculi warrants the inference that spot phenomena, too delicate in their effect on line intensity to be detected with the spectrograph, will be brought to light by the application of spectroheliographs of sufficiently high dispersion.

The question of dispersion is evidently of crucial importance. If the line employed is sensibly narrower than the camera slit of the spectroheliograph, the admixture of light from the adjoining continuous spectrum will tend to blot out the comparatively feeble impression resulting from the faint light of the dark line. The fact that many of the most interesting cases are represented by extremely fine lines thus points to the use of spectroheliographs of great linear dispersion. This consideration, and the desire to photograph the sun with narrow dark lines other than those affected in spots, led to the provision of four prisms for the 5-foot spectroheliograph[1] and the inclusion, in the original plan of the Snow telescope house, of a spectroheliograph of 30 feet (9.14 m) focal length.[2] The latter instrument has not yet been completed. The delay is due in part to difficulty in securing suitable prisms, and in part to the distortion of the Snow telescope mirrors in sunlight. This distortion, while inappreciable during the short exposures that suffice with the 5-foot spectroheliograph, would change the focus and seriously affect the definition of the solar image during the long exposures required with much higher dispersion. As explained in a previous paper,[1] it is hoped that such distortion may be overcome in our new vertical telescope, to which the 30-foot spectroheliograph will be transferred.

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[1] *Contributions from the Solar Observatory*, No. 7, p. 6. This instrument has been used systematically since October 1905 for photographic work with some of the wider dark lines.

[2] *Ibid.* No. 2 p. 14.

Meanwhile, a temporary spectroheliograph of 30 feet focal length has been successfully used with the Snow telescope. This instrument was mounted in the telescope house, between the second mirror of the coelostat and the concave mirror of 60 feet focal length. Instead of the latter, a 5-inch (12.7 cm) objective, of 13 feet (3.96 m) focal length, was used to form the solar image on the collimator slit. The spectroheliograph was built in the Littrow form, with camera slit immediately below the collimator slit; an 8-inch (20.3 cm) objective, of 30 feet focal length, serving at once as collimator and camera lens, and a 6-inch plane grating. As the entire spectroheliograph was supported in a fixed position on piers, it was necessary to cause the solar image to move across the collimator slit, and the photographic plate across the camera slit, at a slow and uniform speed. This was accomplished by mounting the 5-inch image-forming objective and the plate holder (13 feet apart) on arms supported at opposite ends of the movable carriage of the 5-foot spectroheliograph. The driving mechanism of this instrument,[2] supplemented by a counter-shaft for slower speeds, served admirably to give the necessary motion.

On account of the small aperture (only a part of which was used) and the short focal length of the image-forming objective, no appreciable change of focus occurred during the exposures. The small diameter of the solar image (1.4 inches = 3.5 cm) prevented the minor details of structure from being recorded, but enough was shown to serve as a good test of the apparatus and its possibilities.

Several photographs of each spot were made by Mr. Adams and myself on each plate, the first exposure with the camera slit set on the dark line, the other exposures with this slit set on the continuous spectrum, a short distance from the line. In order to eliminate the effect of increased brightness of background, due to the absence of the dark line from the slit in the continuous spectrum photographs, these were repeated, with different speeds of driving.

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[1] *Contributions from the Solar Observatory*, No. 14.

[2] *Ibid.*, No. 7, p. 7.

The first lines tried were those that are strengthened in the umbra and penumbra and on the photosphere, for a considerable distance from spots. The spectroheliograph plates made with such spot lines show the umbra and penumbra much darker than they appear on the plates taken with the light of the continuous spectrum. The apparent diameter of the spot also appears to be considerably increased, doubtless through the inclusion of the dark area surrounding it.

Lines that are weakened in spots, and on the adjoining photosphere, also give definite effects, though the results so far obtained are less satisfactory than in the case of the strengthened lines.

With a large solar image and good conditions of atmosphere, such a spectroheliograph as the one described above is capable of yielding many interesting results, if used systematically with lines affected in spots and with other dark lines. The 30-feet spectroheliograph designed for the "tower telescope" should, however, be much more efficient in many respects than this temporary instrument. The dark areas frequently observed on the sun with the aid of D_3, usually in the vicinity of sun-spots, indicate that spectroheliographic records, made with the light of this line, will also prove of great value. In fact, the promise of future work with this and numerous other lines is so great that the efforts of many investigators, provided with the most powerful instruments, will be required to derive adequate results in this extensive field.

II. STEREOSCOPIC PICTURES OF THE SUN

The application of stereoscopic methods to solar work dates back to the time of De La Rue, who secured interesting results through the combination in the stereoscope of direct photographs of the sun taken at various time intervals, up to two days. These pictures, according to his descriptions, showed the spots as depressions and the faculae as elevated regions. Since his time but little appears to have been done in this field.

In the summer of 1906 I thought it would be of interest to combine, with the aid of our large stereocomparator, various plates made with the Snow telescope and 5-foot spectroheliograph. The results were very satisfactory, showing at once the sphericity of the sun and, to most observers, the protuberant character and cloudlike aspect of the flocculi. If the interval is too short, the effect is imperceptible; if too long, the changes in form of the flocculi, and the large displacements due to the solar rotation, trouble the eye when attempting to unite the images.

The photographs reproduced in Plate XXII were taken on August 22, 1906, at $7^h 26^m$ A. M. and $5^h 21^m$ P. M. During this interval the changes in the form of the flocculi are very noticeable, but do not prevent a fairly satisfactory combination of the images when a glass positive is viewed with a stereoscope. It is doubtful whether the half-tone print will give satisfactory results, though the sphericity of the sun should be evident.

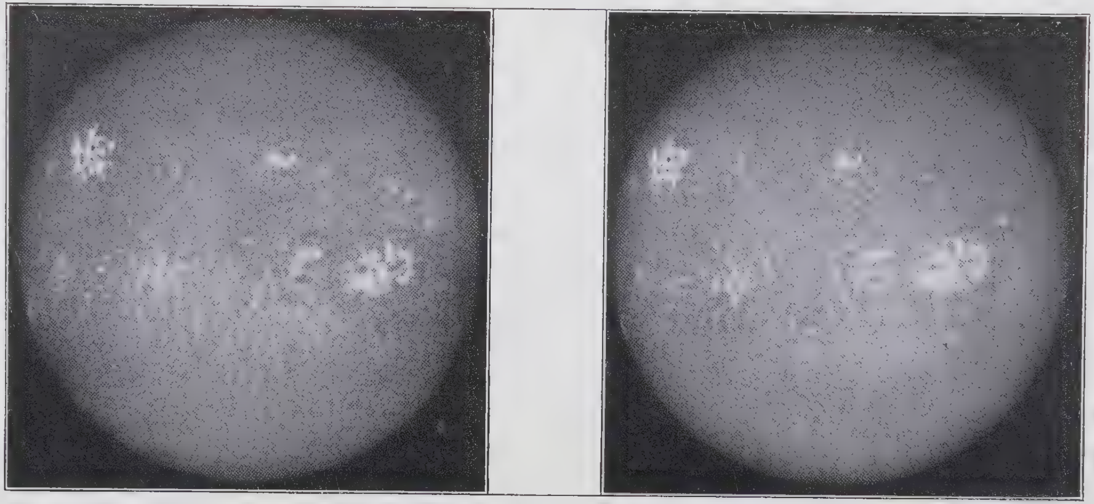
As for the appearance of the flocculi as elevated regions, this is much better shown with the aid of the original negatives, or with positives reproduced on the same scale. The stereocomparator, provided with all facilities for centering and adjusting plates, permits the observations to be made in a most satisfactory manner. It should be stated, however, that some observers see the flocculi as apparent depressions rather than as elevations. This, however, is uncommon.

It seems probable that further studies of this character will bring useful results. It has already been possible to detect in this way linear markings on the solar surface, of great extent, which do not readily strike the eye when plates are examined singly. For purposes of measurement, and the detection of minute differences of form, the monocular eyepiece, with micrometer attachment, which is furnished by Zeiss as an accessory of the stereocomparator, is of course to be employed. It nevertheless appears probable that the stereoscopic method will prove to have certain advantages of its own, which will recommend it to those who are engaged in the study of spectroheliograph plates.

APRIL 1907

PLATE XXII

THE SUN, AUGUST 22, 1906



$5^h\ 21^m$ P. M.

$7^h\ 26^m$ A. M.

Contributions from the Solar Observatory of the Carnegie Institution of Washington, No. 19

Reprinted from the *Astrophysical Journal*, Vol. XXVI, pp. 46–48, 1907

THE ABSENCE OF VERY LONG WAVES FROM THE SUN'S SPECTRUM[1]

By E. F. NICHOLS

During a visit to the Carnegie Solar Observatory in August, 1906, the writer set up a sensitive radiometer and reflected a beam of solar rays on five surfaces of rock-salt in succession. This procedure, according to the method of "residual rays,"[2] is known to give only a narrow spectral region, the mean wave-length of which is 510,000 Ångström units.[3]

The radiometer was of a type earlier described,[4] and the window which admitted the beams from the salt surfaces was a plate of quartz 0.5 mm thick, which has been shown to transmit about 60 per cent. of the energy in this part of the spectrum.[5]

The diagram (Fig. 1) shows the arrangement of apparatus. A beam of sunlight S reflected into the room from a silvered heliostat mirror fell upon a concave silvered mirror M_1 of 26 cm aperture and 75 cm focal length. The converging beam after leaving the mirror M_1 was reflected upon the five polished rock-salt surfaces s_1, s_2, s_3, s_4, s_5, in succession, of which the last surface s_5 was in focus of M_1. After leaving the surface s_5 the diverging pencil fell upon a small silvered collecting mirror M_2, and a secondary solar image was thus formed on one of the radiometer waves a. Exposures were made by raising and lowering a cardboard screen at A.

The solar beam was compared with one from an electric arc lamp L which, with its silvered converging mirror M_3, of 21 cm aperture and 100 cm focal length, could be moved into the position shown by the dotted lines. In this position a beam from the arc traversed the same path as the solar beam with which it was exchanged.

The beam from the arc caused a deflection of the radiometer suspension of 20 scale-divisions, but when a rock-salt plate $2\frac{1}{2}$ cm thick was interposed at *B*, no noticeable deflection could be detected. Rock-salt is very transparent to the region of the spectrum which comprises over 96 per cent. of the total energy emitted by the arc lamp, but is entirely opaque to the residual rays from rock-salt.

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[1] Contributions from the Solar Observatory, No. 19

[2] H. Rubens and E. F. Nichols, *Phys. Rev.*, **4**, 314, and **5**, 152, 1897.

[3] H. Rubens and E. Aschkinass, *Wied. Ann.*, **65**, 247, 1898.

[4] E. F. Nichols, *Phys. Rev.*, **4**, 298, 1897; *Astrophysical Journal*, **13**, 104, 1901.

[5] H. Rubens and E. Aschkinass, *loc. cit.*, p. 249.

The test proved that over 99 per cent. of the energy of the beam under examination lay immediately in the spectral region about 510,000 Å. U.

The solar beam, however, gave a deflection of 17 scale-divisions, which was reduced only by 20 per cent. on interposing the test-plate. As about 10 per cent. of the reduction was due to the regular reflection at the two surfaces of the plate, not more than 10 per cent. could be attributed to absorption proper. As the test-plate surfaces were poor, it is quite possible that no interior absorption took place. On this assumption the experiment shows that *no energy of a wave-length near 510,000 Å. U. reaches the earth from the sun.*

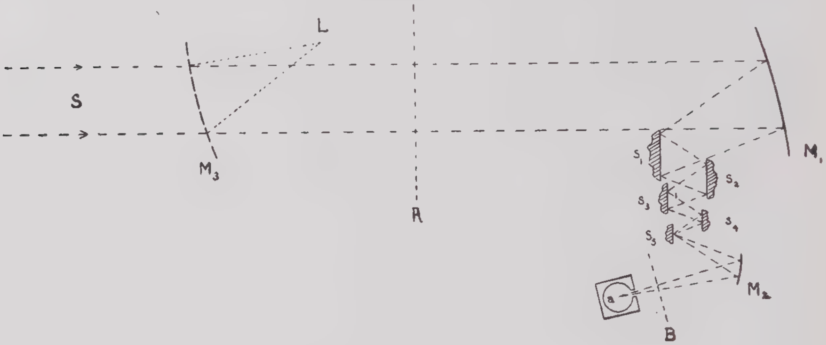

FIG. 1

If, on the contrary, we assume that the questionable 10 per cent. was all due to absorption of long waves, and not to a scattering of shorter waves at the imperfect surfaces of the test-plate, several factors must be taken into account to get at the amount of long-wave absorption in the atmosphere. The approximation will necessarily be a rough one, based on the relative concentrations of the beams from the two sources compared, and their relative temperatures rated as ideal black bodies. In this way it appears that *the maximum atmospheric transmission for the rock-salt waves cannot be greater than 3 per cent.*

In 1897 Rubens and Aschkinass[1] found that the energy of a solar beam after four successive reflections on fluorite surfaces was reduced to zero, thus proving that the opacity of the combined solar and terrestrial envelopes was practically total for wave-lengths near 240,000. At the same time they studied the absorption of water-vapor between the wave-lengths 70,000 and 200,000 and found practical extinction at the latter wave-length. In a paragraph of a later paper, which had until recently escaped my notice, the same writers found water-vapor an absorber of the residual rays from rock-salt and sylvite.[2]

Thus we may assume that the absence of waves 510,000 long in the sun's spectrum to be due to aqueous absorption, even though the tests described in the present paper were made at an elevation of nearly 6,000 feet in a dry climate.

The rôle of water-vapor as an absorber in the earlier infra-red spectrum has long been known, and the later experiments indicate an enormous extension of the region in which the vapor is active. Furthermore, water still shows a strong absorption and some dispersion, even for the shorter electric waves ($\lambda = 6$ to 10 mm). Thus the range of absorption of water, liquid, and vapor is surpassed only among the metallic conductors.

I am greatly indebted to Director George E. Hale for his kindly and whole-hearted co-operation in the present work, and I am no less indebted to the kindness of Dr. Henry G. Gale for constant assistance during the course of the experiments.

COLUMBIA UNIVERSITY, NEW YORK
May, 1907

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[1] *Wied. Ann.*, **64**, 584, 1897.

[2] *Ibid.*, **65**, 251, 1898.

Contributions from the Solar Observatory of the Carnegie Institution of
Washington, No. 20

Reprinted from the *Astrophysical Journal*, Vol. XXVI, pp. 203–224, 1907

SPECTROGRAPHIC OBSERVATIONS OF THE ROTATION OF THE SUN

By WALTER S. ADAMS

The spectroscopic study of the rotation period of the sun's reversing layer has hitherto been confined to visual measures of lines in the less refrangible part of the spectrum. In 1890 Dunér published his classical research upon the subject, including in his discussion results covering the period of three years from 1887 to 1889. Later he supplemented these values with observations made during the years 1899, 1900, and 1901.[1] During the last of these years Halm began the same investigation at Edinburgh, using a fixed horizontal spectroscope and a heliometer to bring the images of the opposite limbs of the sun upon the slit of his instrument. He has since published determinations extending up to 1906[2] and his measures indicate results of the highest accuracy, the probable error for a single observation falling considerably below that of Dunér. In both of these investigations the lines employed were the same, and consisted of a pair of iron lines in the red region of the spectrum having the wave-lengths 6301.72 and 6302.71 on Rowland's scale. The desirability of extending the research to other elements and of employing the obvious advantages of the photographic method as soon as suitable apparatus was available was early realized by Professor Hale at this observatory, and it was at his suggestion that this investigation was commenced.

It is clear that a satisfactory photographic study of the displacements at the sun's limb requires a solar image of considerable size combined with a spectrograph of high dispersion, and sufficient focal length to give full photographic resolution. Both of these are available with the Snow telescope. The concave mirror of this instrument forms an image upon the slit of the spectrograph about 6.7 inches (17.0 cm) in diameter. The spectrograph is of the Littrow, or auto-collimation, type, with a lens 4 inches (10.2 cm) in diameter and 18 feet (5.5 m) focal length employed in conjunction with a plane grating of the same aperture. This grating, which by the kindness of Professor Frost of the Yerkes Observatory has been loaned to the Solar Observatory, is one of the early Rowland gratings, and has 14,438 lines to the inch (570 lines to the mm). It is exceptionally bright in both the third and fourth orders, and gives excellent definition in spite of the great focal length of the spectrograph. The spectra used in this investigation have all been taken in the fourth order, the advantages of the larger scale more than offsetting the greater width of the spectrum lines. The linear scale of the instrument in this order at λ 4200 is about 1 mm = 0.71 Ångström unit.

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[1] *Astronomische Nachrichten*, **167**, 167, 1905.

[2] *Ibid.*, **173**, 273–295, 1907.

The apparatus used to bring the opposite limbs of the sun together on the slit is an adaptation of that first employed by Langley and afterward used by Dunér in his well-known investigations. A pair of small diagonal prisms is mounted on each of two rotating brass arms. The first of these prisms is placed at the outer end of the arm, its mean distance from the center of rotation corresponding to the mean radius of the sun's image, and is capable of adjustment along the arm to correspond with the varying size of the image. A second prism, which receives the beam from the first and reflects it upon the slit, tapers at the end to a width of about 0.5 mm, and is mounted with a point slightly inside the center of this end immediately above the center of rotation of the brass arm. The distance between the edges of the prisms on the two arms is about 0.25 mm, which accordingly represents the distance on the photographic plate between the spectra of the two opposite limbs. The two arms are rotated on a brass frame, and are provided at the ends with pointers by means of which readings are made on a silver position-circle, graduated to half-degrees, and capable of being estimated to tenths. The whole apparatus is mounted upon a brass casting which rests upon a large bracket below the slit of the spectrograph, its position being accurately defined by two taper pins which enter this bracket.

In adjusting this instrument previous to beginning upon the series of observations, great care was taken to secure equal and uniform illumination of the grating surface from the two sets of prisms at all position angles. The simplest method of doing this was to occult the images of the two limbs in succession, and to examine visually from the position of the photographic plate the character of the illumination of the grating. With a narrow slit and comparatively weak illumination this method gives good results. It has, however, been supplemented with photographic tests, the illumination of the collimating lens being photographed on sections of sensitized paper pressed against the rear surface of its cell. The adjustment once made, it has been found necessary to change it on only one occasion, when, owing to a fracture, one of the small diagonal prisms had to be replaced. Since the ratio of aperture to focal length is 1 to 54 in the case of the collimating lens, and 1 to 30 for the image-forming telescope, it is clear that the margin of safety is considerable. It has, however, been the practice to examine visually the character of the illumination previous to each exposure; and it is needless to add that a further valuable check is furnished by the relative density of the pair of spectra upon the photographic plate.

The procedure followed in making the observations has been as follows. The rotation attachment is set in place upon the bracket beneath the slit of the spectrograph, and the image of the sun focused upon the position circle at its edge. The clock driving the coelostat is then stopped, and a spot or other well-defined point upon the sun's surface is allowed to transit across the circle, readings being made at both points of crossing. The mean of three or four such observations, which rarely show a range of more than 0°.3, is used as the line of reference for the determination of the heliographic positions. The pointers on the arms carrying the diagonal prisms are then set at the proper reading of the position circle, the character of the illumination of the grating surface is examined, and the exposure made. The position angle is then changed and the process repeated. On the majority of the plates an exposure has been made for every 15° of latitude between 0° and 75°. This has been done in order to obtain results directly comparable with those of Dunér. A considerable number of intermediate points have been used, however, particularly in high latitudes. At the close of the set of exposures a second series of transits of the spot across the position circle is taken.

The selection of the region of the spectrum most suitable for the work has given considerable difficulty on account of the necessity of securing a sufficiently varied list of lines within a comparatively short extent of spectrum. The portion finally chosen is that extending from λ 4190 to λ 4300. This includes a part of the extremely rich G region, and has the additional advantage of containing the head of the violet carbon fluting, some lines of which it is most desirable to use in the investigation. Another determining feature was the fact that the maximum of sensitiveness of the Seed "process plate" lies not far from this point. This plate has always proved very satisfactory for spectrum work in the blue and violet regions, showing a fine grain and excellent contrast, while at the same time it is appreciably more rapid than the ordinary transparency or lantern-slide plates. The following list of lines was finally adopted:

λ	Element	Intensity	Remarks
4196.699	*La*	2	Much weakened at limb.
4197.257	*C*	2	Slightly weakened at limb
4203.730	*Cr*	2	Strengthened and widened at limb
4209.144	*Zr*	1	Weakened at limb
4216.136	*C*	1	Weakened at limb
4220.509	*Fe*	3	Slightly strengthened at limb. Chromospheric line
4232.887	*Fe*	2	Much strengthened at limb
4257.815	*Mn*	2	Probably weakened at limb
4258.477	*Fe*	2	Much strengthened at limb. Much strengthened in sun-spots
4265.418	*Fe*	2	Slightly weakened at limb
4266.081	*Mn*	2	Perhaps weakened at limb
4268.915	*Fe*	2	Slightly weakened at limb
4276.836	–*Zr*	2	Weakened at limb
4284.838	*Ni*	1	Slightly weakened at limb
4287.566	*Ti*	1	Slightly strengthened at limb. Strengthened in sun-spots
4288.310	*Ti, Fe*	1	Widened at limb
4290.377	*Ti*	2	Slightly weakened at limb. Enhanced line of *Ti*
4290.542	*Fe*	1	Probably weakened at limb
4291.630	*Fe*	2	Much strengthened at limb. Strengthened in sun-spots
4294.936	*Zr*	2	Probably weakened at limb

At the time at which this list of lines was selected the remarkable differences between the spectrum of the center and that of the limb of the sun were not known.[1] It was, however, noted that the lines upon the plates appeared in general rather diffuse and "matt," to use the German expression, and the exposure times were much longer than was to be expected from exposures made on the disk of the sun without auxiliary apparatus. A part of this effect was ascribed to the fact that the light was obliged to traverse some 3 inches (76 mm) of glass in passing through the diagonal prisms. The true cause, however, was not understood until the investigations of Professor Hale and myself showed the radical difference in character and intensity of the spectra of the two parts of the sun's image.

The necessity for selecting only the lines best adapted for measurement has, of course, excluded many interesting lines from the above list, but those given may be regarded as reasonably comprehensive as regards the elements represented, and their behavior at the limb and the center of the sun. The line due to lanthanum is included on account of the high atomic weight of this element, and a similar reason holds for the three lines of zirconium, though in less degree. Carbon is of great interest on account of its position in the chromosphere, and is represented by two lines. The remaining lines are divided among the more important solar elements, iron naturally occupying the most prominent position.

The series of plates amounting to 44 in number included in this discussion was begun in May 1906, and extends to June 1907, a period of nearly fourteen months. Though not distributed uniformly throughout this time they cover the period fairly well with the exception of the interval from July to October, 1906. During these months it was not possible to secure observations on account of the breaking of one of the small central diagonal prisms. In selecting the plates to be measured, only such were chosen as were taken on days when the sky was suitably transparent, and no daylight spectrum was superposed upon the spectra of the two limbs. This point was usually tested by direct visual observation, in the same way as was done by Halm in his series of visual measures in the less refrangible region of the spectrum.

The computation of the heliographic latitudes of the observed points has been made for the most part with the use of De La Rue's reduction tables. These give with the sun's longitude as an argument the position angle of the sun's axis in reference to the north point, and the heliographic latitude of the earth. Since we know the position-circle reading of the point under observation as well as that of the east and west line, the position angle from the north point is known at once, and the computation of the latitude is made simply. For setting the position circle during the observations the table for the position angle of the sun's axis given in the *Companion to the Observatory* has been found very useful. The angle, by the secant of which it is necessary to multiply the observed velocities in order to correct for the departure of the sun's pole from its visible edge, has been taken from the table given by Dunér, except for high latitudes, in which case it has been computed directly. The further correction to be applied for the distance inside the sun's edge from which the light which passes through the slit of the spectrograph has been taken, is found as follows. With the almanac value of the sun's diameter and the scale-setting of the concave mirror of the telescope the value of the linear diameter of the sun's image is computed. The distance between the small windows through which the diagonal prisms receive the light being accurately known, the factor required is readily derived. In practice it has been found preferable to change this distance occasionally rather than to attempt to keep at a fixed distance from the sun's edge as the diameter varied.

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[1] Hale and Adams, *Contributions from the Solar Observatory*, No. 17; *Astrophysical Journal*, 25, 215–225, 1907.

The greater part of the plates have been measured by Miss Lasby of the Computing Division upon the 150 mm measuring machine built by Toepfer. The screw of this instrument has a pitch of 0.5 mm, and the divided head may be read to 0.5 μ. A series of measures upon a fixed distance ruled on a glass plate for every other ten revolutions of the screw from 10 to 280 showed remarkably small periodic errors. At a maximum these amount to 0.3 μ which is much below the limit of accuracy of measurement of spectrum plates. The errors of run of the instrument do not, of course, need to be considered in small differential measurements of this sort. A few of the plates have been measured upon a small comparator built by Gaertner of Chicago. An investigation of the screw of this machine has indicated periodic errors considerably larger than those of the Toepfer instrument, but they still fall below the errors of measurement and may be neglected.

An important consideration to be borne in mind in the measurement of the plates is that of the inclination of the cross-wire in the eye-piece of the measuring instrument. It is evident that unless this coincides accurately with the inclination of the spectrum lines error will be introduced into the measured displacements, since reversing the plate in the ordinary way does not affect the position of the wire in this regard. The objections to attempting to correct by making the second measurement through the glass are obvious. Accordingly, the following procedure has been followed. A solar spectrum has been photographed with a very long slit, having a horizontal line running through its center due to a fine wire stretched across the slit. This plate is used as a standard, and the vertical wire in the eye-piece of the measuring machine is carefully adjusted until it is accurately parallel to the spectrum lines after the plate has been lined up in the usual way with the aid of the horizontal line. It is evident that with the wire adjusted by the use of these long lines any error in its inclination with reference to the very short lines of the rotation spectra must be quite negligible. After this adjustment has been made the cross-wire of the measuring instrument is clamped in position. A change of position of the grating or any inclination of the slit of the spectrograph would, of course, necessitate a new adjustment of the cross-wire, but this has occurred on only one occasion.

In the conversion of the measured displacements into radial velocity use has been made of a small table which combines into one factor for each line the various reduction factors which it is necessary to employ.

It is of course impossible to give the details of the individual plates within the limits of this article. Accordingly, it has seemed best to include two tables of summaries, the first giving the values of the velocities for each plate derived from a mean of all the lines, and the second the value for each line derived from a mean of all the plates. Both the linear and the angular velocities are reduced to the sidereal period of rotation.

The following table furnishes a summary of the results of the separate plates for each latitude. The values given are the means of all the lines measured.

TABLE I

Number of Plate	Date 1906	Number of Lines	ϕ	v km
ω 3	May 3	20	9°.9	2.012
			24.8	1.803
			39.8	1.414
			54.7	0.995
			69.6	0.584
			83.6	0.169
ω 6	May 8	19	10.7	2.026
			25.7	1.789
			40.6	1.390
			55.6	0.981
			70.5	0.575
			84.6	0.146
ω 8	May 19	19	0.8	2.063
			15.6	1.969
			30.6	1.688
			45.5	1.317
			59.2	0.944
			75.4	0.433
ω 19	June 12	20	0.0	2.063
			15.0	1.946
			30.0	1.673
			45.0	1.271
			60.0	0.862
			75.0	0.446
ω 20	June 12	20	0.0	2.071
			15.0	1.932
			30.0	1.659
			45.0	1.262
			60.0	0.856
			75.0	0.439
ω 21	June 12	20	0.0	2.060
			15.0	1.939
			16.0	1.939
			30.0	1.664
			45.0	1.267
			60.0	0.849
			75.0	0.444
ω 23	June 15	20	0.1	2.056
			15.1	1.937
			30.1	1.667
			45.1	1.252
			60.1	0.845
			75.0	0.430
ω 24	June 15	20	0.0	2.071
			15.0	1.939
			30.0	1.672
			45.0	1.265
			60.0	0.858
			74.9	0.440
ω 25	June 15	20	0.0	2.067
			15.0	1.961
			30.0	1.656
			45.0	1.269
ω 25	June 15	20	60°.0	0.848
			75.0	0.414
ω 26	June 16	20	0.2	2.088
			15.0	1.973
			30.0	1.636
			44.9	1.271
			59.9	0.852
			74.9	0.442
ω 27	June 16	20	0.0	2.077
			15.0	1.959
			30.0	1.656
			45.0	1.263
			60.0	0.862
			74.9	0.452
ω 30	Oct. 19	20	0.0	2.109
			14.9	1.966
			29.8	1.695
			44.8	1.293
			59.6	0.876
			74.1	0.488
ω 31	Oct. 19	20	0.0	2.110
			15.0	1.974
			29.9	1.698
			44.9	1.312
			59.8	0.898
			74.2	0.498
ω 35	Nov. 11	20	0.5	2.056
			74.2	0.467
ω 36	Nov. 11	20	0.5	2.078
			14.4	1.977
			29.4	1.683
			44.4	1.277
			59.3	0.889
		19	74.2	0.488
ω 37	Nov. 11	20	0.5	2.082
			14.4	1.975
			29.4	1.689
			44.4	1.276
			59.3	0.881
			74.2	0.472
ω 38	Nov. 11	20	0.5	2.077
			14.4	1.958
			29.4	1.670
			44.4	1.273
			59.3	0.871
			74.2	0.470
ω 39	Nov. 11	20	0.5	2.081
			14.4	1.956
			29.4	1.677
			44.4	1.281
			59.3	0.882
			74.2	0.473
ω 39½	Dec. 18	20	1.2	2.099

TABLE I—*Continued*

Number of Plate	Date 1906–7	Number of Lines	φ	v km	Number of Plate	Date 1907	Number of Lines	φ	v km
ω 39½	Dec. 18	20	15°.2	1.969	ω 61	Feb. 28	16	44°.0	1.261
			30.2	1.696	ω 62	Feb. 28	20	6.0	2.041
ω 40	Dec. 18	20	0.2	2.085				7.9	1.995
			0.2	2.095				15.6	1.944
			15.2	1.962				22.5	1.786
			15.2	1.962				30.2	1.652
			30.2	1.685				38.1	1.510
			30.2	1.689	ω 63	Feb. 28	20	7.2	2.035
ω 41	Dec. 18	20	0.2	2.087				20.6	1.841
			0.2	2.073				28.2	1.672
			15.2	1.950				35.1	1.533
			15.2	1.952				50.7	1.055
			30.2	1.691				43.8	1.280
			30.2	1.679	ω 64	April 7	20	77.5	0.359
ω 46	Dec. 18	20	44.4	1.285	ω 67	April 7	20	77.5	0.360
			44.4	1.282	ω 68	April 7	20	77.5	0.365
			44.4	1.282	ω 69	April 7	20	77.5	0.365
			59.4	0.877	ω 81	April 22	20	67.2	0.642
			59.4	0.868				67.2	0.635
			59.4	0.871				72.5	0.485
ω 48	Dec. 18	20	35.4	1.532				72.5	0.483
			35.4	1.509				79.5	0.326
			44.4	1.294				79.5	0.321
			51.9	1.071	ω 83	May 10	20	63.5	0.749
			51.9	1.076				63.5	0.747
			59.4	0.881				74.4	0.441
	1907							74.4	0.437
ω 50	Feb. 3	20	7.1	2.009				79.2	0.311
			23.0	1.828				79.2	0.303
			37.9	1.510	ω 85	May 30	20	63.8	0.723
			53.7	1.002				63.8	0.728
			69.2	0.596				74.8	0.442
			77.5	0.325				74.8	0.441
ω 55	Feb. 15	20	7.4	2.046				59.8	0.304
			22.3	1.838				79.8	0.306
			38.2	1.458	ω 86	May 31	20	14.8	1.967
ω 56	Feb. 15	20	7.4	2.010				29.8	1.663
			22.3	1.846			19	44.8	1.298
			38.2	1.455			20	64.1	0.750
			53.9	1.045				76.1	0.392
			69.4	0.608				81.1	0.267
ω 60	Feb. 28	20	6.9	2.041	ω 87	June 22	20	8.1	2.024
			6.9	2.045				23.1	1.794
			20.8	1.837				38.6	1.407
			28.4	1.676				52.1	1.053
			35.3	1.510				52.1	1.048
		20	43.6	1.295				59.1	0.857
			50.7	1.088	ω 88	June 22	20	8.1	2.036
ω 61	Feb. 28	18	59.8	0.831				23.1	1.783
		17	65.6	0.676				38.6	1.406
		18	65.6	0.676				52.1	1.063
		17	59.9	0.824				52.1	1.062
		18	50.9	1.102				59.1	0.851

TABLE I—*Continued*

Number of Plate	Date 1907	Number of Lines	ϕ	v km	Number of Plate	Date 1907	Number of Lines	ϕ	v km
ω 89	June 22	20	8°.5	1.990	ω 90	June 22	20	35°.4	1.440
			23.5	1.787				54.5	1.006
			39.0	1.400				53.0	1.063
			52.5	1.077				64.7	0.721
			52.5	1.069	ω 91	June 23	20	6.9	2.011
			59.5	0.856				21.9	1.780
ω 90	June 22	20	6.9	2.044				37.4	1.423
			21.9	1.791				53.0	1.064

The results given in this table have been grouped into mean positions for twelve latitudes, and a summary of the values for these latitudes is found in the latter part of the discussion. In Table II, immediately following, the results are given for the individual lines of the list, the number of plates included under each mean latitude being indicated in the third column of each table. As usual ξ is used to denote angular velocity.

An examination of Table II will lead to several interesting conclusions. The most striking of these is that the two lines due to carbon at λ 4197.26 and 4216.14, and the line due to lanthanum at λ 4196.70, show systematically low values of the angular velocity. The following brief summary indicates more clearly their behavior in this respect, the quantities given being the differences between their values and the mean values for the list.

ϕ	0°.2	7°.7	15°.0	22°.7	29°.7	37°.7	44°.7	52°.7	59°.6	65°.7	74°.9	80°.4
4196.70	0°.0	−0°.1	−0°.2	−0°.1	−0°.1	−0°.1	−0°.2	−0°.3	−0°.4	−0°.3	−0°.7	−1°.1
4197.26	−0.1	0.0	−0.1	−0.1	0.0	−0.2	−0.2	−0.2	−0.2	−0.4	−0.5	−0.9
4216.14	−0.2	0.0	−0.1	−0.1	−0.2	−0.1	−0.2	−0.2	−0.3	−0.3	−0.5	−0.7

In the higher latitudes, of course, a small difference in linear velocity corresponds to a large difference in angular velocity, and the quantitative results are relatively much less certain than in the lower latitudes. Accordingly, while the apparent increase in the size of the differences seems to be marked in the higher latitudes, I do not feel justified at present in concluding that this is an indication that the lower parts of the reversing layer (at which these lines undoubtedly originate for the most part) show a greater retardation

TABLE II

φ	λ	Number of Plates	v km	ξ	φ	λ	Number of Plates	v km	ξ
0°.2	4196.699	21	2.076	14°.74	15°.0	4284.838	23	1.954	14°.36
	4197.257	21	2.070	14.70		4287.566	23	1.958	14.39
	4203.730	20	2.094	14.87		4288.310	23	1.943	14.28
	4209.144	21	2.105	14.95		4290.377	23	1.935	14.22
	4216.136	21	2.057	14.61		4290.542	23	1.954	14.36
	4220.509	21	2.094	14.87		4291.630	23	1.956	14.38
	4232.887	21	2.082	14.79		4294.936	23	1.947	14.32
	4257.815	21	2.092	14.85	22°.7	4196.699	12	1.791	13.78
	4258.477	21	2.080	14.77		4197.257	13	1.796	13.82
	4265.418	21	2.077	14.75		4203.730	13	1.810	13.93
	4266.081	21	2.085	14.81		4209.144	13	1.818	13.99
	4268.915	21	2.074	14.73		4216.136	13	1.791	13.78
	4276.836	21	2.081	14.78		4220.509	13	1.816	13.97
	4284.838	21	2.073	14.72		4232.887	13	1.814	13.95
	4287.566	21	2.072	14.71		4257.815	13	1.823	14.03
	4288.310	21	2.077	14.75		4258.477	13	1.806	13.90
	4290.377	21	2.062	14.65		4265.418	13	1.801	13.86
	4290.542	21	2.071	14.71		4266.081	13	1.823	14.03
	4291.630	21	2.066	14.67		4268.915	13	1.809	13.92
	4294.936	21	2.069	14.69		4276.836	13	1.803	13.88
7°.7	4196.699	14	2.016	14.44		4284.838	13	1.807	13.91
	4197.257	15	2.026	14.51		4287.566	13	1.806	13.91
	4203.730	15	2.049	14.68		4288.310	13	1.801	13.86
	4209.144	15	2.048	14.67		4290.377	13	1.796	13.83
	4216.136	15	2.028	14.53		4290.542	13	1.804	13.88
	4220.509	15	2.032	14.56		4291.630	13	1.799	13.84
	4232.887	15	2.038	14.59		4294.936	13	1.795	13.81
	4257.815	15	2.054	14.72	29°.7	4196.699	24	1.656	13.54
	4258.477	15	2.031	14.55		4197.257	24	1.668	13.64
	4265.418	15	2.028	14.53		4203.730	23	1.686	13.78
	4266.081	15	2.045	14.64		4209.144	24	1.686	13.78
	4268.915	15	2.029	14.54		4216.136	24	1.648	13.46
	4276.836	15	2.028	14.53		4220.509	24	1.685	13.78
	4284.838	15	2.022	14.48		4232.887	24	1.685	13.78
	4287.566	15	2.017	14.45		4257.815	24	1.692	13.84
	4288.310	15	2.017	14.45		4258.477	24	1.681	13.74
	4290.377	15	2.003	14.34		4265.418	24	1.673	13.68
	4290.542	15	2.007	14.45		4266.081	24	1.683	13.76
	4291.630	15	2.010	14.40		4268.915	24	1.668	13.64
	4294.936	15	2.012	14.41		4276.836	24	1.674	13.68
15°.0	4196.699	23	1.938	14.24		4284.838	24	1.673	13.68
	4197.257	23	1.952	14.35		4287.566	24	1.670	13.66
	4203.730	23	1.974	14.52		4288.310	24	1.669	13.64
	4209.144	23	1.975	14.52		4290.377	24	1.663	13.60
	4216.136	23	1.944	14.29		4290.542	24	1.670	13.66
	4220.509	23	1.979	14.56		4291.630	24	1.674	13.68
	4232.887	23	1.968	14.48		4294.936	24	1.669	13.64
	4257.815	23	1.980	14.57	37°.7	4196.699	15	1.442	12.93
	4258.477	23	1.961	14.41		4197.257	16	1.438	12.90
	4265.418	23	1.966	14.46		4203.730	16	1.462	13.11
	4266.081	23	1.964	14.44		4209.144	16	1.461	13.10
	4268.915	23	1.965	14.45		4216.136	16	1.446	12.96
	4276.836	23	1.958	14.39		4220.509	16	1.459	13.08

TABLE II—*Continued*

ϕ	λ	Number of Plates	v km	ξ	ϕ	λ	Number of Plates	v km	ξ
37°.7	4232.887	16	1.461	13°.10	52°.7	4294.936	18	1.061	12°.42
	4257.815	16	1.472	13.20	59°.6	4196.699	21	0.831	11.67
	4258.477	16	1.454	13.04		4197.257	21	0.843	11.84
	4265.418	16	1.458	13.07		4203.730	23	0.858	12.05
	4266.081	16	1.465	13.14		4209.144	23	0.869	12.20
	4268.915	16	1.463	13.12		4216.136	23	0.840	11.79
	4276.836	16	1.459	13.08		4220.509	23	0.860	12.07
	4284.838	16	1.455	13.05		4232.887	23	0.865	12.14
	4287.566	16	1.454	13.04		4257.815	22	0.884	12.41
	4288.310	16	1.457	13.06		4258.477	23	0.870	12.21
	4290.377	16	1.446	12.96		4265.418	23	0.869	12.20
	4290.542	16	1.454	13.04		4266.081	23	0.879	12.34
	4291.630	16	1.452	13.02		4268.915	23	0.861	12.09
	4294.936	16	1.457	13.06		4276.836	23	0.866	12.16
44°.7	4196.699	21	1.256	12.54		4284.838	23	0.858	12.05
	4197.257	21	1.263	12.62		4287.566	23	0.869	12.20
	4203.730	21	1.275	12.74		4288.310	23	0.864	12.13
	4209.144	22	1.296	12.95		4290.377	23	0.854	11.99
	4216.136	22	1.259	12.58		4290.542	23	0.852	11.96
	4220.509	22	1.287	12.86		4291.630	23	0.853	11.98
	4232.887	22	1.290	12.88		4294.936	23	0.863	12.12
	4251.815	22	1.299	12.96	65°.7	4196.699	15	0.676	11.65
	4258.477	22	1.280	12.78		4197.257	16	0.671	11.56
	4265.418	21	1.285	12.84		4203.730	18	0.695	11.98
	4266.081	22	1.289	12.87		4209.144	18	0.698	12.03
	4268.915	21	1.282	12.78		4216.136	18	0.673	11.60
	4276.836	22	1.285	12.84		4220.509	18	0.692	11.93
	4284.838	22	1.280	12.78		4232.887	18	0.698	12.03
	4287.566	22	1.278	12.76		4257.815	18	0.710	12.24
	4288.310	22	1.271	12.70		4258.477	18	0.694	11.96
	4290.377	22	1.271	12.70		4265.418	18	0.696	11.99
	4290.542	22	1.274	12.72		4266.081	18	0.712	12.27
	4291.630	22	1.274	12.72		4268.915	18	0.697	12.01
	4294.936	22	1.282	12.80		4276.836	18	0.692	11.93
52°.7	4196.699	16	1.030	12.06		4284.838	18	0.692	11.93
	4197.257	17	1.036	12.13		4287.566	18	0.694	11.96
	4203.730	18	1.049	12.28		4288.310	18	0.689	11.87
	4209.144	18	1.048	12.27		4290.377	18	0.690	11.89
	4216.136	18	1.036	12.13		4290.542	18	0.694	11.96
	4220.509	18	1.052	12.32		4291.630	18	0.698	12.03
	4232.887	18	1.050	12.30		4294.936	18	0.697	12.01
	4257.815	18	1.065	12.47	74°.9	4196.699	37	0.409	11.16
	4258.477	18	1.055	12.35		4197.257	37	0.415	11.32
	4265.418	18	1.053	12.33		4203.730	36	0.436	11.90
	4266.081	18	1.069	12.52		4209.144	37	0.440	12.01
	4268.915	18	1.052	12.31		4216.136	37	0.416	11.35
	4276.836	18	1.054	12.34		4220.509	37	0.436	11.90
	4284.838	18	1.058	12.38		4232.887	37	0.436	11.90
	4287.566	18	1.055	12.35		4257.815	37	0.449	12.25
	4288.310	18	1.060	12.41		4258.477	37	0.435	11.87
	4290.377	18	1.052	12.31		4265.418	37	0.437	11.92
	4290.542	18	1.057	12.37		4266.081	37	0.449	12.25
	4291.630	18	1.057	12.37		4268.915	37	0.436	11.90

TABLE II.—*Continued*

	λ	Number of Plates	v km	ξ	φ	λ	Number of Plates	v km	ξ
74°9	4276.836	37	0.439	11°98	80°4	4232.887	11	0.292	12.48
	4284.838	37	0.434	11.84		4257.815	11	0.290	12.39
	4287.566	37	0.442	12.06		4258.477	11	0.281	12.01
	4288.310	37	0.439	11.98		4265.418	11	0.287	12.26
	4290.377	37	0.443	12.09		4266.081	11	0.294	12.56
	4290.542	37	0.442	12.06		4268.915	11	0.293	12.52
	4291.630	37	0.443	12.09		4276.836	11	0.283	12.09
	4294.936	36	0.434	11.84		4284.838	11	0.291	12.43
80.4	4196.699	10	0.257	10.98		4287.566	11	0.291	12.43
	4197.257	11	0.250	11.11		4288.310	11	0.285	12.18
	4203.730	11	0.281	12.01		4290.377	11	0.280	11.96
	4209.144	11	0.271	11.58		4290.542	11	0.286	12.22
	4216.136	11	0.267	11.41		4291.630	11	0.293	12.52
	4220.509	11	0.285	12.18		4294.936	11	0.284	12.13

toward the pole than do the higher portions, although some such effect is by no means improbable. In this connection it is interesting to note that the variations in angular velocity found by Halm for the different years covered by his observations were greatest toward the pole.[1] As to the reality of the differences in the rotation rate as given by these lines, and by the mean of the entire list, there can, however, be no question, and the inference is justified that the vapors giving rise to these lines have an angular velocity of rotation which is less than the average rate of the reversing layer. In the lower latitudes the difference amounts to about 0°1 in the daily rate, which would mean a difference of about four hours in the equatorial period of rotation. For both of these elements we have independent evidence tending to show that they lie at a low level in the sun's atmosphere. In the case of carbon this is furnished by direct visual observations, while the great weakening at the limb of the lines of lanthanum and other elements of similarly high atomic weight indicates a comparatively low-lying origin for these elements as well.

Of the other lines in the list the line due to titanium at λ 4290.38 is perhaps the most interesting. This also shows a systematically low value for the angular rotation, although the difference is not so great as in the case of the carbon and lanthanum lines. It is strongly enhanced in the spark, and according to one of the more commonly accepted views of the enhanced lines would lie at a comparatively high level in the sun's atmosphere. It is, however, weakened at the limb, and shows a considerable shift toward the red at the limb as compared with its position at the center.[1] The weakening may perhaps be ascribed to temperature effects, but the pressure-shift and the lower rotational value are strong indications that the line originates in part, at least, at a low level.

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[1] *Astronomische Nachrichten*, 173, 296, 1907

The cases of lines giving high rotational values seem to be hardly so marked as those giving the low values which we have just discussed, although the two lines of manganese at λ 4257.82 and 4266.08 give results which are consistently large. The second of these lines is identified by Frost as present in the flash spectrum, and there is a line in his list close to the position of the first as well, although no identification is made.[2] Neither line, however, is conspicuous in intensity. At the sun's limb, beyond a slight widening, the lines seem to be little affected.

In this connection reference should be made to the work of Jewell at Johns Hopkins University in 1896. While no details of this work have ever been published, some results obtained by him are referred to in an editorial note in the *Astrophysical Journal*.[3] From his investigations Jewell concluded that the outer and inner portions of the sun's atmosphere show a difference in rotation-period amounting to several days, the lower portions having the longer period. The results found here agree with his as regards the direction of the retardation, but it would appear that the amount must be much less than that found by him. Jewell also concluded that at the lower levels the equatorial acceleration is small. So far as we may draw any inference from the result for the carbon and lanthanum lines it would seem to be decidedly opposed to this view. Jewell's conclusion that the carbon lines lie at a very low level is fully confirmed.

After this discussion of the behavior of the individual lines we may return to a consideration of the general results. Although it is clear

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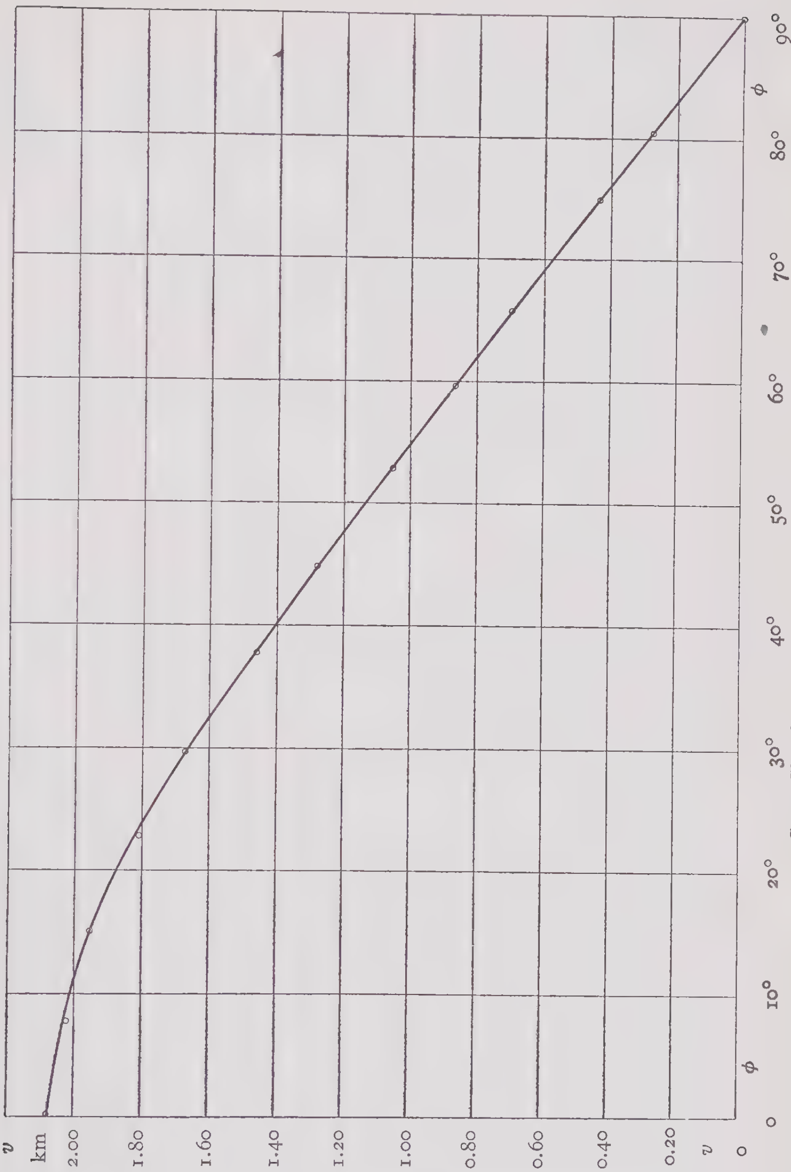
[1] A full discussion of this effect, first found by Halm, and later confirmed and extended by Professor Hale and myself, will be published at an early date. Our observations show that it is almost certainly due to pressure, although it may be modified by other causes as well.

[2] *Astrophysical Journal*, 22, 335, 336, 1900.

[3] *Ibid.*, 4, 138, 1896.



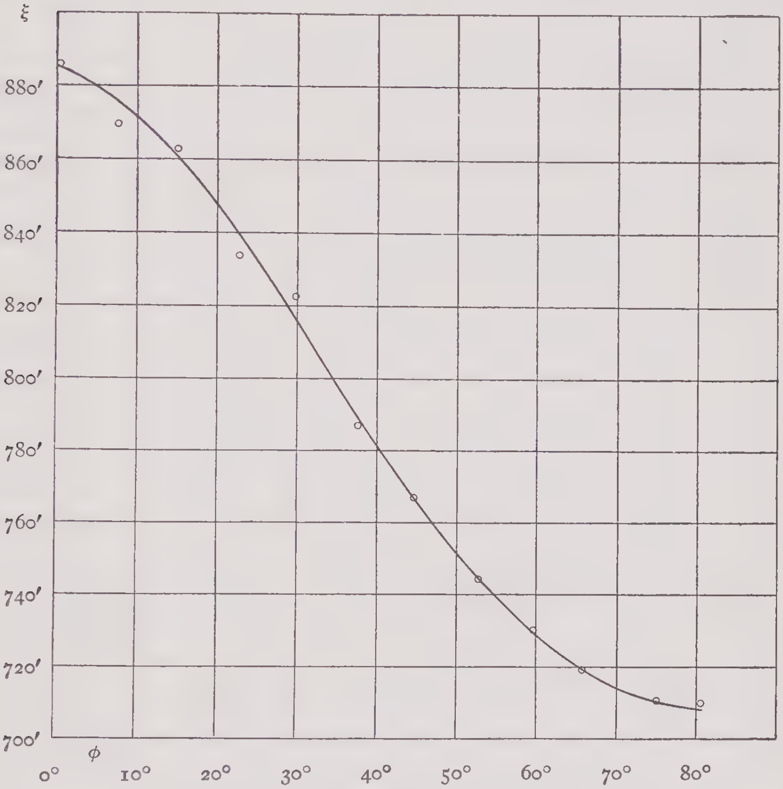
Curve Showing Radial Velocity at Different Latitudes that different lines may give different values for the rate of rotation, it would seem that in order to obtain an average value for the rotational velocity of the reversing layer we can hardly do better than to take a general mean for all the lines. If we form mean values from the quantities given in Table I we are led to the following summary. In the formation of the means such plates as have been measured twice have been assigned double weight.

ϕ	Weight	v km	ξ	Period Days
0°2	21	2.078	14°75	24.39
7.7	15	2.023	14.50	24.83
15.0	23	1.957	14.39	25.01
22.7	13	1.808	13.92	25.86
29.7	24	1.673	13.68	26.32
37.7	15	1.461	13.11	27.46
44.7	23	1.279	12.77	28.19
52.7	18	1.055	12.35	29.15
59.6	24	0.864	12.13	29.68
65.7	20	0.696	11.99	30.02
74.9	33	0.434	11.85	30.38
80.4	11	0.277	11.84	30.40

The two curves which accompany this paper give a graphical representation of the quantities in the table above. In the first and larger curve the radial velocities are plotted as ordinates with the latitudes for abscissae. The second curve represents the change of the angular velocity ξ with the latitude. Both of these curves have been drawn with due regard to the weights of the normal points, which accounts for the apparently abnormal deviation from the curves of the points of lower weight. This is especially true for the two points at 7°7 and 22°7, which are based on comparatively few observations, and which show by far the largest deviations from both curves.

One of the most interesting features of these results is the form of the angular velocity-curve. Starting with a curvature strongly convex upward, its slope rapidly becomes very steep. At about 30° or 35° of latitude there is a point of inflection, and in the higher latitudes it approaches the asymptotic form. In other words, the rate of change of the angular velocity of rotation with the latitude increases from the equator to about latitude 30°, at which point it is greatest. It then begins to decrease, and in the highest latitudes becomes very small. An extrapolation from the curve gives for the daily angular rotation rate at the pole a value of 11°.7, which would correspond to a period of rotation of 30.6 days.

In order to facilitate the comparison of these results with those of Dunér and Halm, a short table is appended giving their values for the latitudes which we have employed here. Their results are taken from the papers already referred to.[1] Since Dunér's values are confined to the six latitudes from 0° to 75°, differing by intervals of 15°, his results are given for these latitudes alone. The much greater number of latitudes employed by Halm, however, makes it comparatively



Curve of Change of Angular Velocity, ξ, with Latitude, φ simple to construct a curve and take from it with sufficient accuracy the values corresponding to the latitudes required. The quantities given in the table have been obtained in this way, and have, of course, a considerable advantage over those given by Dunér and myself, since they have had the benefit of the smoothing-out effect of the curve.

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[1] In his paper Halm has derived mean values from his series of observations for 1901 to 1906, although he ascribes the large systematic differences of the results for different years to actual variations in the period of rotation. His mean values are employed here.

LINEAR VELOCITY				ANGULAR VELOCITY		
ϕ	Dunér km	Halm km	Adams km	Dunér	Halm	Adams
0°2	2.08	2.05	2.08	14°8	14°6	14°7
7.7		2.02	2.02		14.5	14.5
15.0	1.97	1.95	1.96	14.5	14.3	14.4
22.7		1.83	1.81		14.1	13.9
29.7	1.70	1.68	1.67	13.9	13.7	13.7
37.7		1.49	1.46		13.4	13.1
44.7	1.28	1.32	1.28	12.8	13.2	12.8
52.7		1.10	1.05		12.9	12.4
59.6	0.82	0.90	0.86	11.5	12.6	12.2
65.7		0.72	0.69		12.4	12.0
74.9	0.39	0.45	0.43	10.7	12.3	11.8
80.4		0.29	0.28		12.4	11.8

An inspection of these results shows that in the lower latitudes all three series of observations give values which are fairly accordant. Above 30° of latitude, however, Halm's results become larger than those in the other two series, and this continues to be true in the higher latitudes. At about 45° or 50° Dunér's values cross my own, and fall considerably below in the higher latitudes. The general conclusion accordingly, is that the photographic results give a curve of angular velocities which in the higher latitudes is intermediate between those of Dunér and Halm. This curve agrees with that of Halm in showing a falling-off in the rate of the variation in higher latitudes, but the effect seems to begin at a lower latitude than is indicated by Halm's results.

As regards the interesting question of a long period variation in the rotation rate the results given here are, of course, not decisive, since the interval covered by them amounts to rather less than fourteen months. For this interval there seems to be no variation of appreciable size. The fact, moreover, that the values found agree as well as they do with the mean values of Halm for his entire series of observations would seem to furnish some presumption against the existence of such a variation, at least of such magnitude as was found by him.

At present the question must be regarded as one for future observations to decide.

Since the permanency of form of the velocity-curve is thus open to possible doubt, it has not seemed desirable to devote any large amount of attention at present to the consideration of empirical equations which might satisfy it. A preliminary solution by least squares of an equation of the form given by Faye,

$$v=(a-b\sin^2\phi)\cos\phi,$$

showed that the curve could be reasonably well satisfied by an equation of this type, the largest residual amounting to about 0.024 km. The residuals (computed − observed values) were, however, consistently positive in mean latitudes, and consistently negative in high latitudes. This naturally suggested the addition of a term in cos ϕ, giving an equation of the form

$$v=(a-b\sin^2\phi+c\cos\phi)\cos\phi\,,$$

or, in another form,

$$v=(a'+b'\cos\phi+c'\cos^2\phi)\cos\phi\,.$$

A solution by least squares of this equation for the twelve latitudes gave the following residuals:

ϕ	C.−O. km
0°.2	−0.008
7.7	+0.016
15.0	0.000
22.7	+0.013
29.7	−0.007
37.7	+0.004
44.7	−0.004
52.7	0.000
59.6	0.000
65.7	−0.001
74.9	+0.002
80.4	+0.004

The only large residuals are those given by the points of low weight at 7°.7 and 22°.7, and these are by no means excessive. Though an equation involving three constants is, of course, inferior to one containing but two, the very satisfactory size of the residuals given by it, and the simplicity of its form probably justify its use.

In concluding this discussion it will be useful for purposes of comparison with the results obtained from the measures of spot, faculae, and flocculi positions, to add a short table giving the values of the daily angular rotation for every 10° of latitude. These have been taken from the curve and are as follows.

ϕ	ξ	Period Days
0°.0	14°.72	24.46
10.0	14.52	24.79
20.0	14.13	25.48
30.0	13.62	26.43
40.0	13.03	27.63
50.0	12.53	28.73
60.0	12.15	29.63
70.0	11.90	30.25
80.0	11.78	30.56

A comparison of the probable errors of these results with the probable errors of the visual determinations of Dunér and Halm is somewhat difficult on account of the difference in the character of the measurements. In the work of both Dunér and Halm a considerable number of settings of the micrometer wire were made upon each of two lines (by Dunér twelve to twenty-four, by Halm eight), and these series of settings, combined for the two lines, furnish separate observations of the velocity. In the present photographic investigation a smaller number of settings was made upon each of a considerable number of lines, and the values given by all the lines measured on a plate are combined to form a single determination. For general purposes, however, it will be sufficient to compare the probable error in the determination from a single line on the photographic plate, with the probable error from a series of visual observations equal in number to that of the lines on the plate. This evidently gives a decided advantage to the visual results in the comparison, since the mean of two lines is used for them as well as a greater number of settings on each line. On the other hand it is clear that in the photographic results such lines as give systematically large or small values throughout the whole series of observations should be omitted in the formation of the probable error. We have discussed six cases of this sort in connection with Table II, namely, the lines λ 4196, 4197, 4216, 4257, 4266, and 4290.38. If we omit these we have left a total of fourteen lines to each plate. A determination made from several plates taken at random from the series gives as the probable error for a single line,

$$\epsilon = \pm 0.015 \text{ km};$$

or, for the mean value from the plate,

$$\epsilon_0 = \pm 0.004 \text{ km}.$$

To compare with these we have a series of determinations by Halm in 1903[1] averaging fifteen observations for each latitude. He gives for these

$$\epsilon = \pm 0.070 \text{ km}$$

as the probable error of a single observation, and

$$\epsilon_0 = \pm 0.018 \text{ km}$$

as the probable error of the group. Dunér has not given the probable errors for his completed series of observations. For his earlier results they amount to about double those given by Halm.

We are certainly justified in concluding from this comparison that for the same number of measurements the photographic method is capable of furnishing results of higher precision than the visual, at least in so far as inferences of this kind can be drawn from comparisons of probable errors. As in most cases of quantitative spectroscopic work, however, it is probable that in both the visual and the photographic series of observations the effects of small systematic errors begin to be felt before the limits of accuracy defined by the probable errors of groups of results are reached. As regards this class of error it is difficult to conclude with which method of observation the advantage lies. Since the observer is free during the exposure of the photographic plate to do any small amount of guiding necessary to hold the image of the sun in a definite position, the error arising from wandering of the image should be less than in visual measures by a single observer. On the other hand any error which does enter from this source affects all of the lines upon the photographic plate, while in the visual measures it affects each set of pointings only. Perhaps the most valuable general conclusion that can be drawn from the discussion is that the degree of accuracy of measurement attainable on the photographs is so high that it warrants the use of the greatest precautions to avoid small systematic errors.

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[1] *Transactions of the Royal Society of Edinburgh*, **41**, Part 1, 96.

The investigations will be continued with the use of the more powerful apparatus of the tower telescope, and it is hoped that a substantial gain in accuracy may be attained. Among the superior advantages for such work possessed by this instrument we may mention the following: greater linear scale of the plates; a higher degree of accuracy of setting for the various position angles on the sun's image, as well as the possibility of reaching all latitudes on the sun's surface at all times of the year; less liability to changes of temperature on the part of the grating during the exposures; and finally some improvement in the definition of the solar image, and greater freedom from astigmatism and change of focus while the photographs are being obtained.

The more important conclusions derived from this investigation may be summarized as follows:

1. In lower latitudes the values obtained for the rotational velocity agree closely with those of Dunér and Halm. In higher latitudes they are intermediate between the results of these two observers.

2. The rate of change of the rotational velocity with the latitude is greatest at about 30° of latitude. It becomes less in higher latitudes, and beyond 70° is very slight.

3. Different lines give slightly different rates of rotation. Lines of carbon and lanthanum, elements which lie at a low level in the sun's atmosphere, give values for the daily rate about 0°.1 less than the mean values for all the lines. An enhanced line of titanium also gives a slightly lower rate of rotation, while two lines of manganese included in the list give systematically high results.

4. There is no appreciable variation in the rate of rotation during the fourteen months covered by the observations.

5. A comparison of probable errors indicates a substantial gain in accuracy for the photographic results as compared with the visual, so far as accidental errors of measurement are concerned.

I am indebted to Professor Hale for an active interest in this research, and many valuable suggestions during its progress; also to Miss Lasby of the Computing Division for her most efficient performance of the exacting work involved in the measurement and reduction of the large number of plates.

MOUNT WILSON, CAL.
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SUN-SPOT BANDS WHICH APPEAR IN THE SPECTRUM OF A CALCIUM ARC BURNING IN THE PRESENCE OF HYDROGEN

By CHARLES M. OLMSTED

In a recent paper by Hale and Adams,[1] it is shown conclusively that numerous flutings which appear in the spectrum of the flame of a titanium arc are present in the spectrum of sun-spots, the flutings with strong heads degraded toward the red at λ 7054.6, λ 7088.0, and λ 7125.9, being especially noticeable. Recently Fowler[2] has called attention to the coincidence of spot bands near the *b* group with the bands of magnesium hydride. Although titanium and magnesium hydride account for many of the band regions in spots, there are, nevertheless, many bands left unidentified. While examining the spectra of various compounds, and of metals under various conditions, in the hope of identifying more of these regions, a band spectrum of calcium burning in the presence of hydrogen was found. This band spectrum, which so far as I know has not been previously noticed, has without doubt its counterpart in the spectra of spots.

There are two main groups of bands: The stronger one at about λ 6385 (Plate XXIII); the fainter running through the B group. The bands are degraded toward the violet and are built up of rather complexly mixed series of lines. They are similar in appearance to the magnesium hydride bands, and, under low dispersion, present sharply defined heads on the side of greater wave-lengths. The group at λ 6385 has two strong heads (λ 6382.2, λ 6389.3) with less definite and fainter subheads on the red side of these. Heads at approximately λ 6393.0, λ 6398.5, and λ 6407.5 may be noticed.

The band group in the B region, although strong and easily photographed when low dispersion is used, is, however, so weak under high dispersion that I have not succeeded as yet in getting a photograph satisfactory for a detailed comparison with the spot spectrum. It should be remarked, however, that a very much enlarged copy of a negative taken with an instrument of moderate dispersion (a heavy flint 60°-prism used in a Littrow spectrograph of twelve feet [366 cm] focal length) shows beyond a doubt that this group also is in spots. The structure of these bands is in some ways very similar to the group at λ 6385. The discussion of this point is reserved until a stronger high-dispersion photograph is obtained.

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[1] "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Solar Observatory*, No. 15, *Astrophysical Journal*, 25, 75–95, 1907.

[2] "The Origin of Certain Bands in the Spectra of Sun-Spots," *Monthly Notices*, 67, 530–534, 1907.

It seems very probable from the following facts that the spectrum under consideration is due to some compound of calcium and hydrogen:

The bands appear when an arc formed between metallic calcium electrodes burns either in commercial hydrogen or in hydrogen formed from zinc and hydrochloric acid and dried with sulphuric acid; but do not seem to appear when the same electrodes form arc in air.

Also these bands do not appear when dry calcium carbide is used as electrodes in air; but do appear if wet cotton surrounds the electrodes.

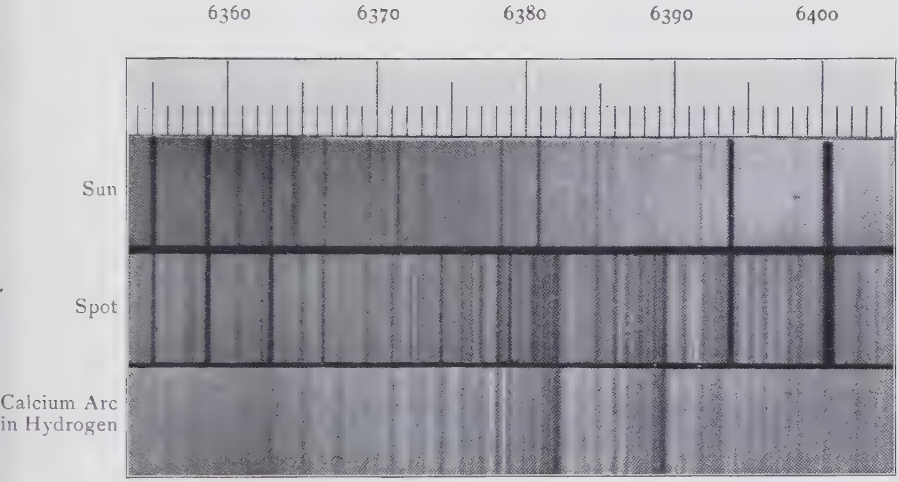
The bands appear when calcium metal electrodes are burned in air if a stream of steam or hydrogen enters the arc through a hole bored in one electrode.

The spectrum from which Plate XXIII was made was obtained by burning a calcium arc of from five to twenty amperes in an atmosphere of commercial hydrogen at atmospheric pressure. The arc was formed between a stationary copper rod as negative electrode and a rotating calcium disk as positive electrode. The first-order spectrum of a Littrow spectrograph of eighteen feet (549 cm) focal length with a six-inch (15.24 cm) grating of 14,438 lines to the inch (5684 lines to the cm) was used. With a slit width of 0.003 inch (0.075 mm) a net exposure of two hours with a Wrattan & Wainwright panchromatic plate was necessary.

It should be mentioned that while testing calcium carbide in air to see if the spectrum were due to the carbide, some bands in the green, due to calcium carbide, were noted. These are beautiful strong bands degraded toward the red; but as they do not appear in spots, their discussion does not belong to this communication.

The following table of wave-lengths indicates the agreement which exists between the individual lines of the bands of the spectrum

PLATE XXIII



ORANGE BANDS COMMON TO THE SPECTRUM OF SUN-SPOTS AND TO THE CALCIUM ARC BURNING IN HYDROGEN

SUN-SPOT		*Ca* IN H_2		NOTES	
λ	Int.	λ	Int.	Spot	*Ca* in H_2
6369.45	6	.39	6	Center of wide blend	Center of wide blend
70.16	4	.10	4	Maximum of wide blend	Maximum of wide blend
70.55	1				
70.80	1	.76	1		Double
71.14	10	.16	8		
71.57	5	.63	1		
72.37	6	.37	5		
72.88	5	.89	5	*Ti* line at 72.86	
73.23	5	.23	4		
73.67	2	.66	1	Wide	Double
74.03	1	.02	1	Double	Double
74.42	14	.42	10		
74.94	2	.99	2		
75.29	2	.31	1		
75.80	6	.80	8		Wide
76.07	2				
76.47	6	.46	4		
76.64	1	.62	1		
77.08	8	.17	5	Wide	Wide
77.39	4			Hazy *Ti* line at 77.27	
78.18	12	.15	12	Double	Double
78.48	2				
79.00	16	.00	10	Wide	Wide
79.57	3	.60	1	*Ti* line at 79.54	
79.93	4	.93	7		
80.23	2				
80.62	10	.62	8	Blurred triplet	Wide
80.97	6			Double	
81.26	8	.26	8		
81.61	8	.65	5		Double
81.96	6	82.02	6		
82.21	16	.25	20		
		82.41	2		
		82.62	1		
82.81	3	.79	2		
82.98	1				
83.38	1				
83.57	2	.56	2	Double	Double
84.02	4	83.97	4		
84.31	4	.31	4		
84.91	9	.91	6	Wide (triplet)	Wide
85.60	3	.57	2		
86.04	12	.04	11	Wide	Wide
86.91	9	.95	8	Maximum measured—has violet wing	
87.31	4	.35	2		
87.68	5	.63	4	*Ti* line at 87.70	
87.84	5	.86	3		
87.91	3	.92	3		
88.71	6	.67	6	Maximum	Maximum
89.02	2	88.98	2	*Ti* line at 88.99	
89.34	16	.33	20	Double	Double
89.79	1				
90.05	2	.00	1		

Sun-Spot		*Ca* in H_2		Notes	
λ	Int.	λ	Int.	Spot	*Ca* in H_2
6390.17	4	.19	4		
90.68	10	.68	10	*Ti* line at 90.65	Wide
91.26	4				
91.68	2	.68	2		
91.94	6	.93	6	*Ti* line at 92.03	
92.35	2	.35	2		
92.61	1				
92.75	3	.80	1		
93.18	4	.18	5		
93.81	50	.80	2	Solar line at 6393.820 [*Fe* 7	
94.48	6	.48	6		
95.00	4	.02	4	*Ti* line at 94.93	
95.31	6	.32	4		
96.03	4				
		96.16	1		
96.25	5	.26	5		
96.58	1	.58	2		
		96.78	1		
96.89	4				
97.07	4	.05	4		
97.58	2				
97.66	6	.68	6		
98.45	9	.44	6	Double	Double
98.49	5	.48	4		
		99.33	2		
99.70	4	.65	3		
		99.84	1		
6400.22	60			Solar line 6400.217 *Fe* 8	
		00.27	6		
00.56	40	.59	2	Solar line 6400.538 *Fe* 2	
01.09	2	.15	2	Wide	Wide
01.56	6			Wide: *Ti* line at 01.48	
02.03	4	.04	4		
02.34	4				
02.49	6	.48	8		
02.94	4	.98	4		
03.58	6	.50	4	*Ti* line at 03.56	
04.32	2	.37	2	Double	Wide

of the calcium arc burning in hydrogen and those of the sun-spot spectrum. The scale of intensities is purely arbitrary, the larger numbers indicating greater intensities. Out of eighty-four spot lines (all that could be distinctly seen between λ 6389 and λ 6405) sixty-two are matched to within 0.05 tenth-meters by band lines of *Ca* in hydrogen. Within this same region there are twelve lines of the calcium spectrum which are not matched to within 0.05 tenth-meters by spot-lines. Probably five of these disagreements are due to errors of measurement greater than 0.05 tenth-meters, the remainder to impurities.

Mount Wilson
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PRELIMINARY CATALOGUE OF LINES AFFECTED IN SUN-SPOTS

REGION λ 4000 TO λ 4500

By WALTER S. ADAMS

INTRODUCTORY NOTE

One of the co-operative investigations set on foot by the International Union for Co-operation in Solar Research was the detailed visual study of the lines affected in sun-spots. The committee in charge of this work concluded that the simplest way to detect possible changes of intensity would be to compare the observed spot lines with the same lines as recorded in a map of the spot spectrum. The preparation of such a map from visual observations would obviously entail much time and labor. For this reason it seemed desirable to make use of the photographs of spot spectra obtained with the Snow telescope at Mount Wilson. Accordingly, a preliminary map was prepared and placed in the hands of the observers taking part in this work. The present paper is the first of a series which will contain a preliminary catalogue of the lines affected on the original negatives, and should prove of service in connection with the map.[1] Since the intensities in the catalogue are mean values, derived from the discussion of several negatives, they naturally possess greater weight than estimates made directly from the map. It is expected that the detailed results from the individual plates will be published later, and it is also hoped that the preliminary map may ultimately be replaced by a more perfect one.

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[1] It is perhaps desirable to emphasize the fact that in our previous publications on the spot spectrum we have made no attempt to give an exhaustive list of the lines affected in sun-spots for any region of the spectrum, but have treated merely some of the more prominent cases of strengthened and weakened lines. As an illustration of this it may be mentioned that in the region $H\beta$ to D a preliminary investigation indicates rather more than 225 lines which are weakened in spots. In a recent study of the same region Mr. Nagaraja of the Kodaikanal Observatory has given a list of 167 weakened lines (*Astrophysical Journal*, **26**, 143, 1907). In this connection it may also be well to state that in our previous discussion of the weakened lines in the sun-spot spectrum on the temperature basis (*ibid.*, **24**, 185, 1906), we have by no means maintained that all the weakened lines are spark lines. On the other hand, so far as our experience goes, it seems to be true without marked exception in the part of the spectrum extending from the red to λ 4000 that all spark lines are weakened. Mr. Nagaraja gives five lines in the region discussed by him which he considers exceptions to this rule. Of the first two of these lines, λ 5169.07 and λ 5169.22, it is the latter

Although the instrument with which the negatives have been obtained, and the procedure followed in making the exposures have been described previously, it may be convenient for the purposes of reference to allude to them here. The spectrograph used was of the Littrow or auto-collimation type with a focal length of 18 feet (5.5 m) and having a 4-inch (10.2 cm) grating with 14,438 lines to the inch (570 lines to the mm). The photographs have all been made in the second order, which gives a linear scale of about 1 mm = 1.5 Å. The spectrograph has been used in conjunction with the Snow telescope, the concave mirror of which forms a solar image about 6.7 inches (17.0 cm) in diameter on the slit. During the exposure of the photographic plate to the spectrum of the spot the light from the photosphere is excluded from the slit, but at the conclusion of this exposure the ordinary solar spectrum is photographed on either side for purposes of comparison. This is readily done by means of an occulting bar which moves across the slit and has an opening of variable size which may be adjusted to the size of the spot under observation. The exposures are timed to give as nearly as possible the same intensity to the continuous spectrum of the spot and of the comparison spectrum. The ratio of the two exposures varies, of course, with the definition of the solar image, the transparency of the sky, and the size and blackness of the spot, as well as the wave-length of the region photographed. Under average conditions at λ 5500 the spot requires about six times as long as the comparison spectrum, while at λ 4000 this ratio increases to about ten or eleven.

The present paper contains a list of the lines affected in sun-spots for the region λ 4000 to λ 4500. It will be followed by other lists giving

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which is the spark line, and it is decidedly weakened in spots; the former, on the other hand, is strengthened, and unless the dispersion of the instrument is sufficient to separate the two lines, it might well appear that the blend is not affected. The third line, λ 5188.87, seems to be distinctly weakened on our plates. The fourth and fifth lines, λ 5502.9 and λ 5621.7, either are not represented in the solar spectrum, or the lines are so faint (not above 000 on Rowland's scale) that conclusions can hardly be drawn as to their behavior.

the results obtained by one or both of us in other parts of the spectrum. Our series of photographs in the ultra-violet may not be completed for some time, and for this reason the present list begins at λ 4000.

The tables are of the same general character as those given by us in previous publications. The intensities are based upon Rowland's scale, and in the few instances in which his values for individual lines seem to need modification notes to this effect are added in the margin. For purposes of identification we have compared our list with the tables of the wave-lengths of arc lines by Hasselberg, and the "enhanced" line tables of Lockyer, the wave-lengths given in the marginal notes being from these sources. In general, only the more obvious identifications are included, and no attempt has been made to present alternative identifications unless they seem to be of special significance as regards the behavior of the lines in the spot spectrum. An extended discussion of this sort belongs rather to a detailed analysis of the results than to the catalogue proper, and we shall hope to enter into this subject farther in a concluding paper.

GEORGE E. HALE
WALTER S. ADAMS

The following is a list of the negatives employed in obtaining the results given in this paper. All of the plates were secured by Mr. Ellerman except L 128, which was taken by the writer.

TABLE I

Plate	Date	Greenwich Spot Number
L 76	1906, June 29	5898
L 77	June 30	5898
L 88	July 2	5898
L 82	July 2	5898
L 83	July 2	5898
L 84	July 2	5898
L 92	July 9	5898
L 94	July 30	5944
L 95	July 31	5944
L 101	Aug. 2	5944
L 128	1907, June 22	6205
L 134	July 19	....

In the case of plate L 134 the Greenwich spot number has not as yet been published.

TABLE II

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4000.61	*Fe*	2	2–3	3	
4001.32	*Mn*, —	3	2	4	
4003.08	—	2	1–2	6	
4003.91	*Ce–Fe–Ti*	3	3–4	3	Widened
4005.86	*V*	3	2–3	3	Spark line of *V*
4006.90	—	2	2–3	3	
06.98	—	1			
4009.02	—	2	6	7	
09.08	*Ti*	3			
4009.29	—	1	0–1	3	
4009.81	*Ti*	1	5–6	3	Much widened
09.86	*Fe*	3			
4010.33	*Ce–Fe*	1	1–2	3	
4010.74	—	3	2–3	3	Rowland's intensity too high: 2 better
4011.56	*Fe*	3	3–4	3	
4012.54	*Ti*, *Ce*	4	3–4	6	Narrow. Spark lines of *Ti* and *Cr*
12.63	*Cr*	0			
4013.80	*Ti–Fe*	3	3–4	3	
4015.53	—	0	0–1	3	Hasselberg gives *Ti* 4015.56
4015.76	—	3	2	3	Narrow. Spark line of *Ni*
4017.93	*Ti*	0	0–1	3	
4018.23	*Mn*	3	9	4	Widened
18.27	*Mn*	4			
4019.20	*Ni–Ce*	1	1–2	3	Widened
4019.45	*Co*	0	0–1	7	Rowland's intensity too high: 00 better
4020.34	—	1	2	3	
20.42	—	2			
4020.55	*Sc*	1	3	8	
20.64	*Fe*	1			
4021.06	*Nd–Co*	3	3–4	8	
4022.02	*Ti–Fe–V*	5 d?	6	3	
4022.37	*Fe*	1	1–2	4	
4023.53	*V*, *Co*	3	2–3	8	Spark line of *Co*
4023.83	*Sc*	2	3	7	
4024.73	*Ti*	3	4	3	
4025.16	*Cr*	0	4	7	Widened to violet. Spark line of *Ti*
25.29	*Ti–Ce*	3			
4026.32	*Cr*	0	1	8	
4026.58	*Mn*	2 N	4	3	
26.69	*Ti*	1			
4027.19	*Co*	1	3	8	
27.25	*Cr*	0			
4027.82	—	1	0–1	7	
4028.50	*Ti–Ce*	4	3	8	Spark line of *Ti*
4030.34	*Fe*	2	2–3	3	
4030.65	*Nd–Fe–Ti*	5	5–6	3	
4030.88	*Mn*	10 d?	11	4	
30.95					
4033.22	*Mn*	8 d?	10	3	Widened
33.34	*Fe?*	1			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4034.64	*Mn*	6 d	8	3	Widened, hazy
4036.52	—	0	0–1	8	
4036.92	*V*, —	1	0–1	7	
4037.27	—	2	2	8	Very hazy. Rowland's intensity [too high: 1 better
4038.94	—	2	2–3	3	
4040.09	*Fe*	1	1–2	3	
4040.24	*Fe?*	2	1–2	3	
4040.79	*Fe*	3	4	4	Hazy. Rowland's intensity too [high: 2 better
4041.43	*Fe*	3	9	5	Widened
41.52	*Mn*	5			
4044.06	*Fe*	3	4	6	
44.14	—	2			
4045.54	*Co*	5	5–6	3	Difficult: in shade of following line
4045.98	*Fe*	30	32	6	Probably slightly strengthened
4047.82	*Y*	0 N	1–2	7	
47.96	—	0 N			
4048.82	*Zr*	1	7	6	Widened
48.91	*Mn–Cr*	5			
4050.83	*Fe*	2	1–2	3	
4051.49	*Cr–V*	0 Nd?	0–1	3	
4052.60	*Mn*, *Fe*	2	4	3	Rowland's intensity too high: 4 better for total
52.65	—	3			
4053.98	*Cr–Fe–Ti*	3	2–3	7	
4054.59	*Zn*	0	1–2	3	Strengthened to red
54.71	*Sc*	00 N			
4054.96	*Fe*	2	4	6	
55.02	*Fe*	3			
4055.70	*Mn*	6	7	6	
4056.50	*Fe*	1	2	3	
56.60	—	0			
4057.37	*Co*	1 N	4–5	4	Not fully separated from following line
57.50	*Fe*	3			
4057.67	—	7	5	4	
4059.08	*Mn*	3	4	6	
4059.54	*Mn*	1 Nd?	2	3	Widened to red
59.65	—	0			
4059.87	*Fe*	2	1–2	7	
4060.42	*Ti*	1	2	8	
4060.64	—	0	00	3	Nearly obliterated
4060.92	—	0	0–1	3	
4061.78	*Mn*	2 Nd	2–3	6	Fringe on violet side
4062.10	—	2	1–2	3	
4062.60	*Fe*	5	5–6	5	Widened
4064.36	*Ti*	1	2	5	
4065.24	*Mn–Ti*	2 d?	3	7	
4066.52	*Co*	2	3	7	
4067.14	*Cr–Fe*	5	5–6	3	
4067.43	*Fe*	3	4–5	6	
4068.14	*Fe–Mn*	6	7	6	Very hazy, widened
4068.69	*Co*	0	0–1	3	
4070.43	*Mn*	3	4–5	7	Much widened

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4073.92	*Ce, Fe*	4	5	4	
4075.26	— *Nd*	2 N	1–2	6	Rowland's intensity too high: 1 better
4076.10	*Fe*	3	2–3	7	
4077.88	*Sr*	8	8	6	Winged
4078.52	*Zr–Fe*	4	8	7	
78.63	*Ti*	3			
4079.34	*Fe*	2	6	4	Widened
79.39	*Mn*	3			
4079.57	*Mn*	3	3–4	3	
4080.00	*Fe*	3	4	7	
4080.37	*Fe, Nd, Cr*	3	3–4	3	
4081.38	*Zr, Ce*	0	2	4	
81.42	—	1			
4082.26	*Fe*	2	2–3	3	
4082.59	*Sc–Fe–Ti*	3	4	8	
4083.10	*V–Mn*	4	5	7	Widened
4083.72	*Fe*	2	7	4	
83.78	*Mn, Y*	4			
4084.65	*Fe*	5	5	7	Perhaps winged
4085.47	*Fe*	4	5–6	7	Widened
4086.47	*Co* —	3 d?	4	7	Much widened
4086.86	*La*	1	1–2	3	
4089.37	*Fe*	3	4	6	
4090.73	*V*	1	2	8	
4091.11	*Ce* —	3	3–4	4	
4091.71	*Fe*	3	3–4	6	
4092.82	*V, Ca*	3 d?	4–5	8	
4095.09	*Ca?*	4	5	8	
4095.42	*Mn*	0	0	6	
95.51	—	0			
4095.63	*V*	0	1	6	
4096.37	—	1	1–2	6	
4097.24	*Fe*	3	3	7	Very broad and hazy
4097.61	—	000	0	3	
4097.81	—	0	0–1	6	
4098.12	—	0	0–1	3	Seen as fringe on following line
4098.34	*Fe*	5	4–5	6	
4098.69	—	4	7	7	
98.75	—, *Co?*	2			
4099.21	—	0	1–2	6	Very broad
99.33	*Ti*	00			
4099.94	*V*	2	4	8	
4100.32	*Fe*	2	1–2	6	
4100.50	—	0	1	3	
4100.90	*Fe*	4	4–5	5	
4102.00	*H, In*	40 N	20	7	$H\delta$ is both narrowed and weakened
4102.32	*V*	0	1	7	
4103.10	*Si, Mn*	5	6	4	
4104.91	*Co, V*	00	0	7	
4105.32	*V*	2	4	8	Broad
4105.98	—	000	00	3	

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4106.42	*Fe*	2	3–4	7	
4106.58	*Fe*	2	1–2	6	
4106.8			0	3	Perhaps a blend of two faint solar lines
4107.65	*Ce–Fe*	5	6	4	Widened, hazy
4108.29	—	1	1–2	4	
4108.69	—	2	3	7	
4109.22	*Fe*	3	3–4	5	Narrow
4109.90	*V*	2	7	7	Much widened
09.95	*Fe*	3			
4111.15	—	1	00	3	Nearly obliterated
4111.51	*Ce?*	1	1–2	4	
4111.94	*V*	4	6	8	Very broad
4112.48	*Fe*	2	3	7	Much widened
4112.87	*Ti*	1	2	8	
4113.07	—	1	3	8	Narrow
13.12	*Fe*	3			
4113.68	—	000 Nd?	1	7	Broad patch
4114.27	—	00 d	0–1	3	
4114.61	*Fe*	4	5	6	Widened
4115.33	*V*	3	4–5	8	
4116.63	*V*	1	3–4	8	
16.71	*V, Fe?*	0			
4116.97	*Nd?*	00	0	3	Seen as fringe on 4116.86
4117.11	—	0	0–1	3	
4117.59	—	000	0–1	3	Broad patch
4118.01	—	2	3	7	Widened
4118.31	*V*	0	0–1	7	
4118.71	*Fe*	5	6	5	
4118.93	*Co*	4	7	5	
19.05	*Fe*	2			
4120.78	—	0	1	3	Broad patch. Hasselberg gives *V* 4120.69
4121.48	*Cr–Co*	6 d?	7	5	
4121.96	*Fe, Cr*	3	3–4	5	
4122.82	—	1	1–2	3	
4123.38	*La*	1	0	5	
4123.54	*Cr*	0	3–4	8	
23.66	*Ce, V–Mn*	1			
23.71	*Ti*	000			
4123.91	*Fe*	5	4	4	Rowland's intensity too high: 4 better
4124.64	—	0	0–1	3	
4125.53	—	000	0	3	
4125.78	*Fe*	3	3	5	Narrow
25.85	—	1			
4126.20	—	000	5	5	
26.34	*V–Fe*	4			
4126.67	*Cr*	2	3	7	Rowland's intensity too high: 1 better
4127.01	—	1	2	7	
27.07	*Cr*	00			
4128.25	*Ce–V, —*	6 d	8	6	

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4128.46	—	00	0	3	
4128.89	—	2	0	7	Nearly obliterated; fringe on red side probably due to 4129.13
4129.34	*Ce* —	3	3-4	6	
4129.62	—	2	1-2	7	
4130.11	—	0	3	7	
30.20	*Fe*	2			
4130.60	—	0	3	6	
30.80	*Ba*	2			
4131.27	*Ce, Mn*	1	2	4	Hasselberg gives *V* 4131.32
4131.51	*Cr*	0	1	7	
4132.10	*V*	2	14	6	Widened to violet
32.24	*Fe–Co*	10			
4132.69	—	3	2	7	
4133.06	*Fe*	4	4-5	5	
4133.76	*Fe*	2	0	7	Rowland's intensity too high: 1 better. Fringe to violet
4134.49	*Fe?*	3	7-8	6	
34.59	*Fe?*	3			
4135.84	—	00	1-2	7	
35.92	*Zr*	0			
4136.68	*Fe*	4	5	7	
4137.16	*Fe*	6	7	4	Spark line of *Mn* falls here
4137.43	*Ti, Mn*	0 Nd?	3-4	7	Widened to violet
37.57	—	2			
4138.13	—	0	0-1	3	Broad
4138.52	—	0 N	6	8	
4139.52	—	00	1	4	Broad patch. Hasselberg gives *V* 4139.39
39.61	—	000			
4140.09	*Fe*	6	6-7	3	
4140.56	—, *Fe?*	3	3-4	7	Much widened, perhaps winged
4140.91	—	0	0-1	3	
4142.02	*Fe*	4	4-5	3	Widened
4143.57	*Fe*	4	5-6	5	Narrowed in spot
43.66	—, *Mo*	2			
4144.04	*Fe*	15	13	6	Narrowed in spot
4146.22	*Fe*	3	3	6	Fringe on red side
4146.84	—	0 N	1	7	Broad
4147.14	—	2	1	7	
4147.50	—	2	1-2	3	Rowland's intensity too high: 1 better
4147.84	*Fe*	4	6-7	7	
4148.55	—	00	0	3	
4149.53	*Fe*	4	5	6	Widened
4149.92	—	2	3	7	
4150.41	—	4	4-5	7	Rowland's intensity too high: 3 better
4150.61	*Co*	1	0	7	
4151.13	*Ce–Zr, Ti*	1	1-2	6	
4152.24	—	1	4-5	5	
52.34	*Fe*	3			
4152.69	*C?*	00	0-1	3	Hasselberg gives *V* 4152.81
52.76	*Zr*	00			
4152.93	*Cr, La*	0	00-0	3	

TALBE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4153.22	*Cr*	00	0–1	7	
4153.78	*Co*	0	0–1	3	
4153.97	*Cr*	1	6	6	
54.07	*Fe*	4			
4154.67	*Fe*	4	4–5	7	Widened
4154.98	*Fe*	4	4–5	5	
4155.21	—	00	0	2	
4155.68	—	00	1	3	Broad patch
55.80	—	00			
4156.07	—	1	0–1	3	
4156.39	*Zr*	1	2	4	
56.47	—	3			
4157.95	*Fe*	5	5–6	3	
4158.54	*C?*	0	1	7	
58.59	*C?*	00			
4159.35	—	5	4	7	
4159.80	*Ti*	0	1	4	
4160.53	—	2	3	7	Widened. Hasselberg gives *V* 4160.57
4161.37	*Zr* —	2	1–2	3	
4161.68	—	4	3–4	7	Widened. Spark line of *Ti* falls here
4161.96	*Sr*	1	00	7	Nearly obliterated. Spark line of *Sr*
4162.28	—	00 N	0	3	
4162.62	*C*, —	1 N	0–1	3	
4162.82	*Ce*, *C*	1 N	0–1	3	
4163.07	—	00	1	6	
63.14	—	000			
4163.64	—	0 d	0–1	3	
4163.82	*Cr–Ti*, —	4	3–4	4	Spark line of *Ti*
4164.80	—	0	2	7	Hasselberg gives *Ti* 4164.80
64.94	—	0			
4165.28	—	0	1	7	
4165.55	*C*, *Fe*	3 d	2–3	3	Narrow
4165.76	—, *Ce*	1	0–1	7	
4166.16	*Ba*	0	1–2	6	
66.26	—	00			
4166.36	—	00	2	6	Hasselberg gives *Ti* 4166.45
66.46	—	0			
4167.44	—	8	6	6	
4168.02	*Ce–Fe*	2	4–5	6	
68.13	*Ni*, *C*	2			
4168.63	—	00 N	3	7	Strengthening due to 4168.63
68.78	—	2			
4169.11	—	2	2–3	3	
4169.93	—	2	2–3	3	
4171.07	*Fe*	4	4–5	3	
4171.85	*C*, *Fe?*	2	2–3	6	
4172.07	*Ti*, *Fe*	2	1–2	6	Spark line of *Ti*
4172.21	*Al*	1	4–5	7	
72.30	*Fe–Ce*	2			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4172.80	—	2	6	5	Weakened to violet, probably strengthened to red
72.92	*Fe*	4			
4173.14	—	1	0–1	6	
4173.62	—	3	4–5	7	Spark line of *Fe*
73.71	—	3			Spark line of *Ti*
4174.10	*Fe*	3	4	6	Weak to red. Spark line of *Ti* at 4174.20. Hasselberg gives *V* 4174.18
74.24	—	0			
4174.97	*Cr*	0	5–6	7	
75.08	*Fe*	4			
4175.29	—	1 N	0	7	
4175.81	*Fe*	5	5–6	3	
4178.22	—	2	1	7	
4179.02	—	3	2	7	Spark line of *Fe*
4179.54	*V*, —	3 d?	3–4	7	Widened
4180.56	—	1	1–2	6	
4181.35	—	0	0–1	3	
4181.92	*Fe*	5	5–6	4	
4182.14	—	2	1–2	7	Narrow
4182.92	—	2	1–2	4	Narrow
4183.17	—	1	0–1	5	
4183.48	*Zr*	1 N	2	7	Weak to red. Spark line of *V* at 4183.60
83.62	—	2 N			
4184.16	—	4	3	7	Rowland's intensity too high: 3 better
4184.47	—	2	1–2	7	Narrow. Spark line of *Ti* at 4184.40
4185.06	*Fe*, *Cr*	4	5–6	7	
4186.28	*Ti*	1	2	7	
4186.78	*Ce–Zr*	2 N	1–2	6	
4187.20	*Fe*	6	7	6	
4187.94	*Fe*	5	9	6	
88.02	—	3			
4188.89	—	4	3–4	5	
4189.14	*C*, —	1	2–3	4	
89.26	—	1			
4189.98	*V*	0 Nd?	1	7	Rowland's intensity too high: 00 better
4190.29	*Cr*	0 N	1–2	6	
90.40	*C*	0			
4190.87	*C*, *Co*	1 Nd?	2–3	8	
4191.60	*Fe*	6	7–8	7	Winged
4191.84	*Fe*	3	3–4	6	
4192.56	*C*	00 N	00–0	3	
4192.73	—	2 N	1	7	
4194.89	*C*, —	1	3	6	Very broad
95.01	*Cr*	1			
4195.49	*Fe*	5	5–6	6	
4195.68	—	1	3–4	7	
95.78	*Fe–C*	2			
4197.26	*C*	2	3	7	Widened to red
97.39	*Cr*	0			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4197.81	—	00	1	6	Hasselberg gives *V* 4197.77
97.90	—	00			
4198.22	*Fe*	2	2–3	4	
4198.40	—	4	7	4	
98.49	*Fe*	4			
4198.80	*Fe*	3	3–4	6	
4199.27	*Zr–Fe*	5	6	4	Very hazy
4200.04	—	1 N	4	7	
00.15	*Fe*	2			
00.26	*Cr*	00			
4200.95	*Ti*	1	2	7	
4201.09	*Fe*	3	3–4	4	
4202.20	*Fe*	8	10	6	Winged
4203.62	*Ti*	00 N	3–4	7	
03.73	*Cr*	2			
4204.88	—	1	2	5	
04.92	—	2			
4205.19	—	1	2	7	Widened
05.24	—	1			
4205.70	—	2	2–3	5	
4206.74	—	1	5	6	Rowland's intensity too low: 5 better for total
06.86	*Fe*	3			
4207.29	*Fe*	3	3–4	7	
4208.77	*Fe*	3	3–4	7	
4209.98	*V*	1	2	7	
4210.49	*Fe*	4	8–9	6	Widened
10.56	—	3			
4211.13	—	3 N	2–3	3	
4211.51	*C–Cr*	0 N	0–1	4	
4211.90	*Mn, C*	0	1	6	Hasselberg gives *Ti* 4211.85
4212.05	*Zr–*	2	1	7	
4213.81	*Fe*	3	3–4	7	Narrow
4215.58	*Fe*	2	8	3	Spark line of *Sr*
15.70	*Sr*	5 d?			
4216.35	*Fe*	3 d?	4–5	7	Widened
4216.76	—	1 N	0–1	3	
4217.72	*La, Fe–Cr*	5 d?	5–6	3	
4218.56	— *Zr*	1 Nd	1–2	6	
4220.51	*Fe*	3	4	6	
4221.63	—	1 N	1	4	
21.74	*Cr*	0			
4222.38	*Fe*	5	6	6	
4223.64	—	1	1–2	3	
23.74	—	1			
4224.34	*Fe*	4	5	3	Hasselberg gives *V* 4224.30
4224.67	*Cr–Fe*	3	4	7	
24.79	*Ti*	00			
4225.02	—	2 N	1–2	7	Spark line of *Cr*
4225.62	*Fe*	3	3–4	5	
4226.90	*Ca*	20 d?	25	8	Very difficult line. Widened and winged
4228.10	—	1 N	0–1	3	

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4229.68	*Fe*	2	2–3	3	Widened to violet
4229.93	*Fe*	3	4	4	Difficult
4232.76	*V*	00	3–4	9	
32.89	*Fe*	2			
4233.33	*Mn*	4	3	8	Strong spark line of *Fe* falls here
4133.77	*Fe*	6	7	7	
4234.17	*Co, V*	0 N	0–1	8	Rowland's intensity too high: 00 better
4234.71	*Zr*	0 N	1	8	Hasselberg gives *V* 4234.70
4235.30	*Mn*	2	6	4	
35.45	*Mn*	3			
4238.19	*Fe*	3	3–4	8	Widened
4239.52	—	2	2–3	8	
4239.89	*Fe, Mn*	3	9	5	
40.01	*Fe*	3			
40.12	—	1			
4240.54	*Fe*	2	4	8	Hasselberg gives *V* 4240.53
40.62	—	1			
4240.87	*Cr*	1	1–2	3	
4241.28	*Fe–Zr*	2	3	8	
4241.68	—	00 N	1	8	Broad patch
41.87	—	00 N			
4242.32	—	0	1	4	
4242.54	—	2	3	8	Spark line of *Cr* at 4242.54
42.62	—	2			
4243.98	—	2	1–2	3	Narrow
4245.42	*Fe*	4	8	7	Probably winged
45.52	—	2			
4247.00	*Sc*	5	6	5	
4247.46	—	1	6	4	Hasselberg gives *V* 4247.46
47.59	*Fe*	4			
4247.73	—	0	00	8	
4248.48	*Ti*	00	2	8	Widened to violet
48.58	—	1			
4249.10	—	2 N	1–2	8	
4250.29	*Fe*	8	9	5	
4252.39	—	00	1–2	9	
52.47	*Co*	0			Broad
4252.78	—	0 N	1	5	Weak to violet. Spark line of *Cr* at 4252.80
52.92	—	1 N			
4253.16	—	1	0–1	8	Spark line of *Mn*
4253.36	—	1	1–2	3	
4254.50	*Cr*	8	10	7	Widened: probably winged
4255.66	*Fe, Cr*	1	2–3	5	
55.79	—	1 N			
4256.29	*Ti*	0	2–3	4	Very broad
56.37	—	1			
4257.82	*Mn*	2	2–3	6	
4258.32	—	1 N	0–1	3	
4258.48	*Fe*	2	4	9	
4259.46	—	1 Nd?	2	3	Hasselberg gives *V* 4259.46
4260.64	*Fe*	10	9	4	Apparently narrowed in spot

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4261.68	— *Cr*	2	3	7	Widened to red
61.75	*Ti*	00			
4262.09	—	1	0–1	8	Spark line of *Cr* at 4262.15
62.14	—	1			
4263.29	*Ti, Cr*	2	3	8	
4264.37	*Fe*	3	4	4	
4264.90	*Fe*	2	1–2	3	
4265.83	*Ti*	0	0–1	8	
4266.08	*Mn*	2	2–3	8	
4266.78	—	0	0–1	3	Rowland's intensity too high: 00 better
4267.12	*Fe*	3	3–4	7	
4268.78	—	0	3–4	7	Hasselberg gives *V* 4268.78
68.92	*Fe*	2			
4269.45	—	0	000	3	Nearly obliterated. Perhaps spark line of *Cr*
4269.90	—	2	3	8	
70.02	—	2 N			
4271.93	*Fe*	15	15	7	Very hazy. Probably narrowed in spot
4272.70	*Ti*, —	1	2	8	
4274.75	*Ti*	2	12	8	Much widened to violet
74.96	*Cr*	7 d?			
4277.15	*V*, —	1 N	1–2	6	
4277.69	—	2 d?	3	8	Much widened
4278.39	*Fe–Ti*	3	3–4	6	Narrow
4279.01	*Ti*, —	1 N	1–2	7	
4279.87	—	2 Nd?	1	3	
4280.56	*Cr*	1	2	8	Broad
4280.94	—	1	0–1	3	
4281.26	*Mn*	2	2–3	6	Narrow
4281.53	*Ti*	0	1–2	8	
4282.13	—	2 N	1–2	3	
4282.56	*Fe*	5	6	3	
4282.86	*Ti*	0	0–1	8	
4283.17	*Ca*	4	5–6	9	
4283.90	—	000	0	3	
4284.22	*Mn, V*	0	0–1	3	Seen as fringe on following line
4284.38	—	2 Nd?	1	9	Spark line of *Cr*
4284.99	—	1	0–1	3	Rowland's intensity too high: 0 better
4285.16	*Ti*, —	2	2–3	8	
4285.52	—	1	3–4	4	
85.60	*Fe*	3			
85.69	—	1			
4286.17	*Ti*, —	2	3–4	8	Narrow
4287.57	*Ti*	1	2	8	
4288.31	*Ti, Fe*	1	2	4	
4288.89	—	(00 N)	1	3	Evident error in Rowland's intensity. Map shows strong line here. Spot intensity is on basis of 2 in sun

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4289.12	—	1	4–5	8	
89.24	*Ti*	2			
4289.52	*Ca*	4	5	8	
4289.88	*Cr*	5	8	8	*Ti* line probably weakened.
90.08	*Ti*	1			
4290.38	*Ti*	2	1–2	6	Narrow. Spark line of *Ti*
4291.11	*Ti*	3	3–4	8	
4291.28	*Ti*	2	2–3	3	
91.38	—	1			
4291.63	*Fe*	2	3–4	8	Widened
4292.14	*Cr, V*	0	0–1	8	Difficult. Seen as fringe on following line
4292.21	—	1	2	5	Spark line of *Mn* at 4292.35
92.29	—	2			
4292.45	—	2	2–3	7	
4293–19	—	2	4	8	
93.27	—	3			
4294.20	*Ti*	2	9	8	Spark line of *Ti*
94.30	*Fe*	5			
4295.19	—	3 d?	4–5	8	
95.38	—	3 Nd?			
4295.91	*Cr, Ti*	2	3–4	8	Narrow
4296.74	—	3	3	5	Spark line of *Fe* at 4296.72
96.84	*Zr?*	1			
4297.37	—	2	3	5	
97.45	—	2			
4297.68	—	1 N	0–1	5	
4297.91	*Cr, V*	0	0–1	8	
4298.14	*Ti*	1	4	8	
98.20	*Fe*	2			
4298.36	—	1	0–1	3	
4298.83	*Ti*	2	3	8	
4298.97	—	2	1	3	
4299.15	*Ca*	3	4	9	
4299.41	*Ti, Fe*	4	5	3	
4299.80	*Fe, Ti*	2	3	9	
4299.99	—	1 N	0–1	3	
4300.21	*Ti*	3	2–3	9	Spark line of *Ti*. Rowland's intensity too low: 4 better
4300.48	—	1 N	0–1	3	
4300.73	*Ti*	2	3	8	
4300.99	—	1	0–1	7	
4301.16	*Ti*	2	8	8	Weak on red edge; *Ti* line strengthened
01.26	—	4			
01.33	—	1			
4301.90	—	0 Nd?	00–0	3	
4302.08	*Ti*	2	1–2	4	Spark line of *Ti*
4302.69	*Ca*	4	6	9	Probably winged
4303.34	—	2	1	8	Spark line of *Fe*
4303.58	—	1 N	0–1	3	
4303.99	—	2	4	8	
04.10	—	4			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4304.42	—	1	0–1	3	
4304.55	—	1	0–1	3	
4304.73	*Fe*, —	2	1–2	6	
4305.27	—	1	0–1	7	
4305.48	—	1	3–4	5	Spark line of *Sr*
05.61	*Fe*,*Sr*,*Ti*, *Cr*	3			
4306.08	*Ti*	4	5–6	8	
4306.86	—	2	3	8	
07.02	—	2			
4307.91	*Ca*	3	10	8	Violet component probably strengthened, red weakened. Spark line of *Ti* at 4308.10
08.08	*Fe*	6			
4309.06	—	1	2–3	7	
09.20	*Fe*	2			
4309.54	*Fe*	3	3–4	7	
4309.79	—	1	1	5	
09.88	—	1			
4309.99	—	0	1–2	7	Hasselberg gives *V* 4309.95
10.07	—	0			
4310.27	—	2	1	7	
4310.54	—	2	2–3	4	
10.63	—	1			
4310.86	—	2 N	2–3	6	
4311.06	—	1	1–2	6	
11.15	—	1			
4311.61	—	2	2–3	5	Spark line of *Mo* at 4311.71
11.67	—	2			
4312.25	—	2	2	4	
12.31	—	1			
4313.03	*Ti*	3	2–3	7	Spark line of *Ti*
4213.80	—	2 Nd?	1–2	3	
4314.25	*Sc*	3	3–4	7	
4314.96	*Ti*	1	2–3	8	
4315.14	*Ti*	3	8	6	Spark line of *Ti*
15.26	*Fe*	4			
4316.96	*Ti*?	1	0–1	8	Spark line of *Ti*
4318.82	*Ca*, *Mn*?	4	6	8	Winged. Hasselberg gives *Ti* 4318.83
4320.66	—	0	1–2	7	
20.76	—	00			
4321.12	—	2	1–2	7	Possibly spark line of *Ti*
4321.81	*Ti*	0	1	8	
4323.39	—	2 Nd?	1	5	
4324.01	—	3	2	5	
4324.57	—	2 N	1–2	4	
4325.15	*Sc*	4	6	7	Widened to red
25.31	*Ti*, *Cr*	1			
4325.94	*Fe*	8	8	6	Apparently narrowed in spot
4326.52	*Ti*	0	1	7	Narrow
4327.27	*Fe*	3	2–3	3	
4328.08	*Fe*	2	2–3	6	Much widened: very hazy
4328.77	—	0 N	00–0	8	

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4329.45	—	0 N	0	3	
29.56	—	0 N			
4330.19	*V*	0 N	2	9	
4330.40	—	1	0	7	
4330.57	—	0	00–0	3	Spark line of *Ti* at 4330.50
30.61	—	0			
4330.87	*Ti, Ni*	2	1–2	8	Spark line of *Ti*
4331.81	*Ni*	2	2	7	Very narrow line in spot. Measures show no change
4332.99	*V*	0	2	9	
33.08	—	0			
4335.10	*La*	0	1	7	Broad. Hasselberg gives *Ti* 4334.98
4337.22	*Fe*	5	7	8	Winged
4337.72	*Cr*	3	4–5	8	
4338.08	*Ti*	4	3	9	Spark line of *Ti*
4338.43	*Fe*	1	2	9	
4339.62	*Cr*	4	6	8	
4339.88	*Cr*	3	4	8	
4340.30	*Cr*	0	0–1	7	
4340.63	*H*	20 N	8	8	*H*γ is both weakened and narrowed
4341.17	*V*	0	2	9	
4341.53	*Ti?*	2	1	8	Spark line of *Ti*
4342.35	—	0	1	3	Broad patch
42.48	—	00			
4343.37	*Cr*	2	4–5	7	
43.43	*Fe*	2			
4343.86	*Fe*	2	2–3	3	
4344.13	—	1 N	0	3	Rowland's intensity too high: 0 better. Spark line of *Mn*
4344.45	*Ti*, —	2	1–2	7	Spark line of *Ti*
4344.67	*Cr*	4	6	8	
4345.05	—	0	00	3	
4345.25	—	00	0–1	3	Broad patch
45.40	—	0000			
4346.28	—	00	00–0	3	Hasselberg gives *Ti* 4346.26
4346.45	—	1	0–1	9	
4346.99	*Cr*	1	1–2	9	Rowland's intensity too high: 0 better
4347.40	*Fe*	1	2	9	
4348.50	—	1 N	0–1	7	
4349.11	*Fe*	2	2–3	3	
4351.00	*Ti*	1	0–1	9	Spark line of *Ti*
4351.22	*Cr*	3	5	8	
4351.93	*Cr*	5	11	7	Strengthening very doubtful. Spark line of *Fe* at 4351.93
52.08	*Mg*	5 Nd?			
4352.91	*Fe*	4	7	9	Widened to red
53.04	*V*	0			
4355.26	*Ca?*	2	3	9	Perhaps winged
4356.06	—	0	2	9	Strengthening due mainly to violet component. Hasselberg gives *V* 4356.10
56.16	*Ni*	0			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4356.53	—	0	00	4	
4356.77	—	0	0–1	6	Widened to red
4359.65	*Ni*	0	5	4	Spark line of *Zr*
59.78	*Cr*	3			
59.91	*Zr*	0			
4360.45	—	1	0–1	4	
4360.64	*Ti*	1	1–2	7	
4362.91	—	0 N	00	3	
4363.27	*Cr*	1 N	1–2	4	
4363.46	—	0 N	00–0	4	Rowland's intensity too low: 1 better
4363.63	—	0	1–2	8	Very broad. Hasselberg gives *V* 4363.69
63.77	—	0			
4365.17	—	000	00	3	
4366.06	*Fe*	2	2–3	3	
4367.22	—	000	0	3	Hasselberg gives *V* 4367.24
4367.75	*Fe*	5	6	8	Weak at red edge. Spark line of *Ti*
67.84	*Ti*	2			
4368.07	*Fe*	2	2–3	7	Narrow
4368.22	—	00	0	3	Hasselberg gives *V* 4368.25
4369.05	*Ti*	00 Nd?	0	3	
4369.57	—	1	0	6	
4371.14	*Zr*	1	1–2	7	Spark line of *Zr*
71.22	—	1			
4371.44	*Cr*	2	3–4	7	
4372.50	—	0 d?	0–1	7	Very broad. Hasselberg gives *Ti* 4372.54
4372.90	—	0	0	6	
73.01	—	0			
4373.42	*Cr*	1	2–3	7	Hasselberg gives *V* 4373.40
4373.73	*Fe*	2	1–2	5	Narrow
4374.98	*Zr*	0	3–4	4	
75.10	*V, Mn*	2			
4375.73	—	0	0	5	
75.82	—	0			
4376.11	*Fe*	6	8	6	Probably winged
4377.39	—	2 N	1–2	6	
77.53	—	0 d?			
4378.42	—	2 Nd?	1–2	5	
4379.40	*V*	4	7	6	Very broad
4380.32	*Co*	2 Nd?	1	6	
4380.88	—	2 Nd?	1	5	Broad
4381.27	*Cr*	0	0–1	5	Hazy, broad
4382.85	*Mn*	0	1–2	6	
82.93	—, *Fe*	2			
4384.48	—	1	0	4	
4384.87	*V*	3	4–5	6	Much widened
4385.14	*Cr*	2	3	6	
4385.55	—	2	0–1	5	Spark line of *Fe*
4387.01	*Ti?*	1	0	7	Spark line of *Ti*
4387.22	—	1 N	0	6	Possibly spark line of *Pb*
4388.06	*Fe, Co*	2	2–3	4	Widened

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4388.89	—	0	0	3	
89.03	—	0 N			
4389.41	*Fe*, —	2	3	6	
4390.15	*V*	2	4	7	
4391.12	*Fe*	2	2–3	3	Weak on red edge. Spark line of *Ti*
91.19	*Ti*	1			
4391.82	*Co*	0	3	7	Weak on violet edge
91.92	*Cr*	1			
92.03	*Co*	0			
4392.24	*V?*	1 N	1–2	7	
4393.44	—	0	1	7	
4393.69	—	1 Nd?	0	5	
4393.97	*V?*	0	1–2	6	
94.09	*Ti*	0			
4394.22	*Ti?*	2	1–2	5	Narrow
4394.94	—	00	0–1	3	Hasselberg gives *V* 4394.98
95.02	*Zr*	00			
4395.20	*Ti*	3	2–3	7	Narrow. Spark line of *Ti*
4395.41	*V*, *Zr*	2	3	7	
4396.01	*Ti*	1	0–1	6	Spark line of *Ti*
4397.12	—	1 N	0–1	4	
4399.94	*Ti*, *Cr*	3	2–3	6	Spark line of *Ti*
4400.56	*Sc*	3	3–4	6	
4400.74	*V*	1	3	7	
4401.18	—	1 N	0–1	4	Possibly spark line of *Pb*
4403.35	—	1	0–1	6	
4404.43	*Ti*	1 N	1–2	4	
4404.93	*Fe*	10	9	6	Apparently narrowed in spot
4406.81	*V*, —	2	4	7	
4407.81	*V*	2	8	7	
07.87	*Fe*	4			
4408.36	*V*	2	3–4	7	
4408.58	*Fe*	3	7	7	Very broad
08.68	*V*	2			
4409.41	—	0	00	5	Widened to red
4409.68	—	1	0–1	4	
4410.68	*Ni*	2	1–2	3	
4411.24	*Cr* —	1	1–2	3	Widened. Spark line of *Ti* falls here.
4412.09	—	1	0	6	
4412.30	*V*	00	2	6	Hazy
12.42	*Cr*	0			
4413.76	—	1	0	6	
4415.29	*Fe*	8	7	4	Apparently narrowed in spot
4415.72	—	3	2–3	6	Narrow
4416.64	*V*	0	2–3	7	
4416.98	—	2	1	6	Narrow
4417.45	*Ti*	0	1–2	7	Broad
17.58	*Co*	00			
4417.88	*Ti*, —	3	2–3	6	Spark line of *Ti*
4418.50	*Ti*, —	1	0–1	5	Greatly widened. Rowland's intensity too low: 2 better

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4419.94	*Mn*	00 N	1–2	7	Widened to red
20.10	*V*	00 N			
4420.45	—	0	00	6	
4421.73	*V*	0	2–3	7	Very broad
4421.93	*Ti*	00	0	3	Perhaps spark line of *Ti*
4422.10	—	1	00–0	6	
4422.98	*Ti*	0	1	7	
4423.30	*Fe*	1	2	7	Broad. Hasselberg gives *V* 4423.32 and *V* 4423.41
23.43	*Cr*	0 N			
4424.01	*Fe ?*—	2	1–2	3	Narrow
4424.46	*Cr*	0	1–2	6	Hasselberg gives *Ti* 4424.58
24.53	—	00			
4425.61	*Ca*	4	5–6	7	Winged
4426.20	*Ti*	0 Nd ?	2	7	
4427.27	*Ti*	2	3	7	
4427.48	*Fe*	5	7	6	Winged
4428.71	*V–Cr*	1 d ?	2	7	
4429.96	*V*	00	1	7	
4430.36	*Fe*	1	0	7	
4430.52	—	00	00–0	3	
4430.78	*Fe*	3	3–4	3	
4431.30	—	0 N	00	5	
4431.52	—	0	0–1	6	Hasselberg gives *Ti* 4431.46
4432.74	*Fe*	1	1–2	4	
4434.17	*Ti*	0 Nd ?	1–2	7	
4435.13	*Ca*	5	7	7	Winged
4435.32	*Fe*	2	3	5	
4435.85	*Ca*	4	6	6	Winged
4436.31	*V*	0	1–2	7	
4436.75	—	00	0	6	Hasselberg gives *Ti* 4436.75
4437.11	*Fe–Ni*	2 d ?	1–2	4	Narrow
4437.73	—	0	00	6	
4438.01	*V*	0	2	7	
4438.51	*Fe*	1	1–2	4	Very much widened
4440.05	*Fe*	1	2	4	Narrow
4440.52	*Ti*	00	1	6	
4440.99	—	1	0–1	6	
4441.15	*Fe*	0	0	6	
41.26	—	0			
4441.43	*Ti*	00	0	6	
4441.88	*V*, —	3 Nd ?	5	7	Very broad
4443.00	*Fe*	1	1–2	6	Narrow
4443.98	*Ti*	5	4	7	Spark line of *Ti*
4444.38	—	0	2–3	7	Rowland's identification *V–Ti* for 4444.57 evidently belongs to this line. Hasselberg gives both *V* and *Ti* here
4444.73	*Fe, Ti*	2	1–2	6	
4445.64	*Fe*	1	2	7	
4447.30	*Mn, Fe*	2	2–3	4	
4447.89	*Fe*	6	8	6	Winged
4449.31	*Ti*	2	3	7	

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4450.65	*Ti?*	2	1–2	6	Narrow. Spark line of *Ti*
4451.09	*Ti*	1	2	6	
4452.17	*V*	0 N	2	7	
4453.17	*Mn*	1	1–2	3	
4453.49	*Ti*	2	3	7	
4453.88	*Ti*	1	2	6	
4454.55	*Fe*	3	3–4	4	
4454.95	*Ca, Zr*	5	7	6	Winged
4455.48	*Mn, Ti*	2	3	6	
4455.98	*Mn*	2	7	7	Winged
56.06	*Ca*	3			
4456.79	*Ca*	2	3–4	7	Perhaps winged
4457.60	*Ti, V, Zr*	2	5–6	6	Strengthened to violet
57.71	*Mn*	2			
4458.24	*Fe?*	2	1–2	6	
4459.52	*Cr*	1	1–2	4	Widened
4459.92	*V*	1	2–3	7	
4460.39	*V*	0	4	7	Rowland's intensity too low: 3 better for total
60.46	*Mn*	1			
60.52	—	0			
4461.82	*Fe*	4	6	6	Much widened
4462.16	*Fe–Mn*	3 Nd?	3–4	7	Widened
4463.57	*Ti–Ni*	0	2	6	Widened to red
63.70	—	00			
63.84	*Ti*	0000			
4464.62	*Ti?*	2	1–2	6	Narrow. Spark line of *Ti*
4464.84	*Mn*	2	3–4	3	
64.94	*Fe*	1			
4465.98	*Ti*	1	2	7	Rowland's intensity too high: 0 better
4466.73	*Fe*	5	6	6	Widened, hazy
4468.66	*Ti*, —	5	4–5	7	Spark line of *Ti*
4469.32	*Ti*	1	0–1	6	
4469.54	*Fe*	4	4	4	Narrow, probably winged
4469.87	*V*	00	0	7	
4470.30	*Mn*	1	1–2	6	
4471.41	*Ti*	0	2	7	
4471.72	—	00 N	1–2	7	Very broad
71.85	—	0			
71.97	—	00			
4472.88	*Fe*	1	2	4	Widened to red. Rowland's intensity too low: 2 better for total
72.97	*Mn*	0			
4473.10	*Ni?*	0	00	6	
4474.21	—	00	0	4	Hasselberg gives *V* 4474.21
4475.03	*Ti*	0	2–3	7	
4475.47	*Cr*	00	0	6	
4476.18	*Fe*	4	8	4	Perhaps winged
76.25	*Ag*	3			
4477.23	—	00	0	3	
4478.19	—	0	0–1	3	
4479.78	*Fe*	1	2	6	Widened to red
79.88	*Ti*	00			

TABLE II—*Continued*

λ	Element	Intensity Rowland	Intensity Spot	Number of Observations	Remarks
4480.31	*Fe*	1	2	6	
4480.75	*Ti, Ni*	0 N	0–1	6	
4480.99	—	0	00–0	3	
4481.30	—	0	000	6	Nearly obliterated. Rowland's intensity too low: 1 better
4481.44	*Ti*	1	2	6	
81.52	—	0			
4482.34	*Fe*,—	5	11	6	Much widened
82.44	*Fe*	3			
4482.90	*Ti–Fe*	1	2–3	6	Very hazy
83.04	*Cr*	00			
4484.39	*Fe*	4	4–5	3	
4488.22	*Fe–Cr*	0	2	6	Widened to violet
88.30	—	1			
4488.49	—	1	0	7	Spark line of *Ti*
4488.93	*V*	0000	2	7	Widened to violet
89.08	*Fe*	1			
4489.26	*Ti*	0	3	6	Widened to violet. Spark line of *Fe* at 4489.35
89.35	—	2			
4489.91	*Fe*	4	6	6	
4490.25	*Mn–Fe*	3 N	3–4	6	
4491.57	—	2	0–1	6	Spark line of *Fe*
4491.82	*Cr–Mn*	0	0–1	6	Rowland's intensity too high: 00 better
4492.48	*Cr, Fe*	0	0–1	6	Much widened
4493.70	—	1	0–1	6	Fringe on red side
4494.22	—	1	1–2	6	Much widened
4494.74	*Fe*	6	7–8	6	
4495.18	*Ti*	00	0	6	
4496.32	*Ti*	1	2–3	7	
4497.02	*Cr*	3	4–5	6	Hasselberg gives *V* 4497.03
4497.84	*Ti*	0 N	1–2	7	
4498.90	*Cr*	0	0–1	6	Rowland's intensity too high: 00 better
4499.07	*Mn*	1	1–2	6	Rowland's intensity too low: 2 better
4499.31	—	1	0–1	6	

MOUNT WILSON, CAL.
November 1907

Contributions from the Mount Wilson Solar Observatory, No. 23
Reprinted from the *Astrophysical Journal*, Vol. XXVII, pp. 204–212, 1908

THE TOWER TELESCOPE OF THE MOUNT WILSON SOLAR OBSERVATORY[1]

By GEORGE E. HALE

In a previous paper[2] I have outlined some of the conditions to be met in designing a fixed telescope for solar research. The change of figure of the mirrors on exposure to the sun, and the disturbance of the definition caused by heated currents of air rising from the ground, are the principal difficulties encountered. Since exposure to sunlight ordinarily produces actual bending of the mirrors, the use of very thick disks is naturally suggested. Again, since currents of warm air rising from the earth rapidly become mixed with cooler air at higher levels, a point of observation even 50 or 60 feet above the ground offers very definite advantages. Accordingly, the design adopted and described in my paper consists of a coelostat with very thick mirrors, mounted at the summit of a skeleton steel tower about 65 feet in height. The second mirror used with the coelostat stands near the center of the tower and sends the beam vertically downward through a 12-inch (30.5 cm) visual objective, by Brashear, of 60 feet (18.29 m) focal length (Fig. 1). The image of the sun is thus formed by this objective at a point about 5 feet (1.5 m) above the level of the ground, within a small building standing at the base of the tower.

It will be seen that the arrangement described comprises the following points of advantage: (1) great thickness of mirrors, to reduce astigmatism and rapid change of focal length; (2) the use of an objective, instead of a concave mirror (as employed in the Snow telescope), giving the shortest possible path between the coelostat and the focal plane and greatly decreasing the change of focal length experienced with a concave mirror; (3) the use of a vertical beam of light, with less probability of disturbance across the wave-front than in the case of a horizontal beam. Moreover, this type of telescope is well adapted for use in connection with an underground laboratory, in which power-

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 23.

[2] *Contributions from the Solar Observatory*, No. 14; *Astrophysical Journal*, **25**, 68–74, 1907.

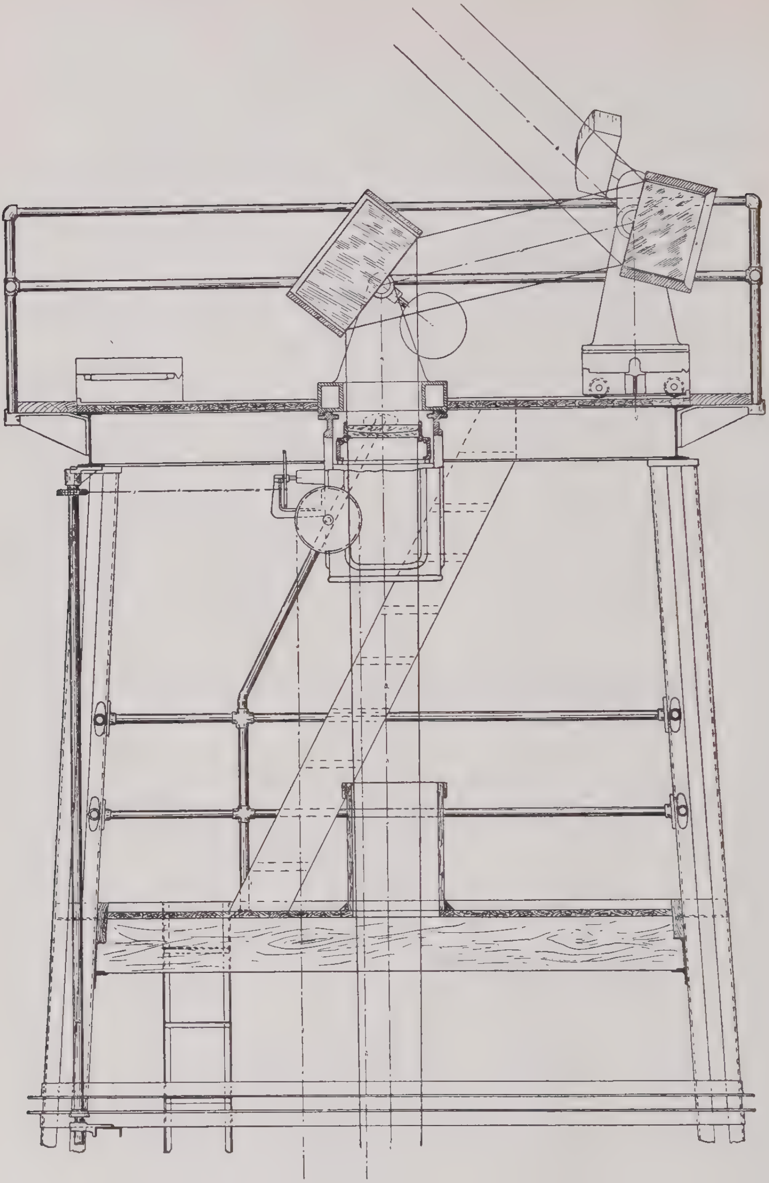
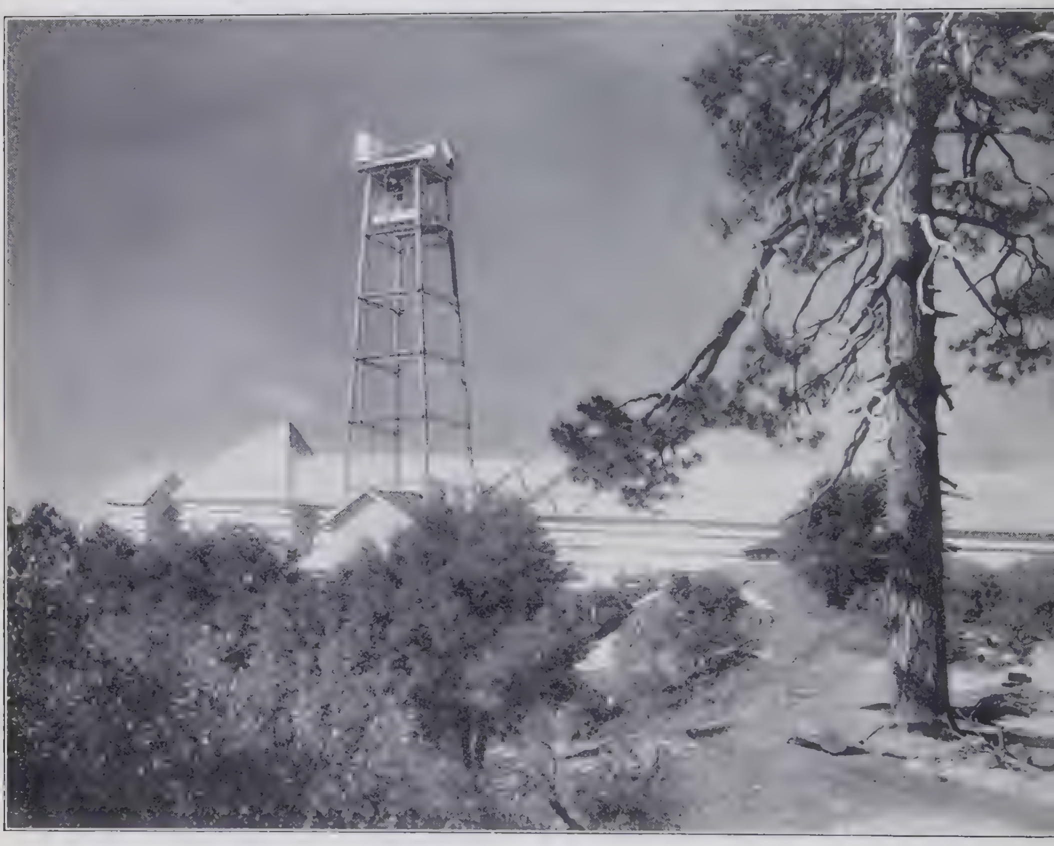


FIG. 1.—Section through upper end of Tower

PLATE XXIV



The Tower Telescope

The Snow Telescope appears in the background ful spectrographs and other instruments requiring constancy of temperature and freedom from vibration can be mounted.

Soon after the publication of the paper cited, a special grant from the Carnegie Institution permitted the construction of the "tower" telescope to be undertaken. On account of the great pressure of work in our own instrument shop, it was not feasible to construct here the coelostat and the mounting for the second mirror and objective, or the Littrow spectrograph. Accordingly, the former were built by Brashear, and the spectrograph by Gaertner, from our working drawings. The steel tower, purchased from the Aermoter Company of Chicago, was set up on Mount Wilson last July. The coelostat mirror, 17 inches (43.2 cm) in diameter and 12 inches (30.5 cm) thick, and the elliptical mirror, also 12 inches thick, with major axis of 22¼ inches (56.5 cm) and minor axis of 12¾ inches (32.4 cm), were both made in our optical shop under the direction of Mr. Ritchey. All of the other parts of the instrument, including the platform at the summit of the tower, the rails on which the coelostat carriage slides, the vertical shaft and driving mechanism for moving the 12-inch objective (when the instrument is used with a spectroheliograph), the house at the foot of the tower, supports for the spectrograph, etc., were built by our own workmen.

Plate XXIV is reproduced from a photograph of the tower telescope.[1] In the original design an outer tower, covered with canvas louvers, was provided to protect the inner one from the wind. However, on account of the importance of avoiding convection currents, which might result from heating of the outer tower, it was thought best to try the experiment of using the inner tower alone, without wind protection. This has proved so satisfactory that it is hardly likely the outer tower will be added. In a windy country a single tower would not be stable enough, but on Mount Wilson, where the average wind velocity during the best observing hours, especially in summer, is very low, the present arrangement seems likely to suffice. The use of a number of steel guy ropes is of course essential.

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[1] This photograph was taken from a point northeast of the tower, and shows the Snow telescope house in the background. The small shelter standing on the south side of the platform at the summit of the tower is placed over the coelostat when the telescope is not in use.

Fig. 1 shows, in general outline (from the north), the arrangement of the apparatus at the summit of the tower. The coelostat carriage stands on rails, which permit it to be moved north and south. As the best definition is obtained with the low morning or afternoon sun, the apparatus is designed to give the greatest efficiency at such times. When observing the morning sun, the coelostat stands on the west rails, its position in a north-and-south line being determined by the declination of the sun for the date in question. When it is to be used for afternoon observations, the coelostat is transferred, by means of a carriage rolling on east-and-west rails, to the rails east of the second mirror. The second mirror is then turned so as to face the coelostat mirror, and the beam sent vertically downward as before.

The object-glass, which stands just below the second mirror, is mounted in a support which can be moved vertically, for focusing, by a steel tape controlled by a hand-wheel near the focal plane (Plate XXV). It can also be moved in an east-and-west direction by means of a screw connected with a vertical shaft driven by an electric motor in the house at the foot of the tower.[1] The image of the sun can thus be made to move at a uniform rate across the collimator slit of a spectroheliograph, the same motor being employed to move the photographic plate, at the same rate, across the camera slit.

Plate XXV shows the slit-end of the 30-foot spectrograph, in the house at the base of the tower. The underground chamber in which the spectrograph stands is a circular well, 8½ feet (2.6 m) in diameter and 30 feet (9.1 m) deep. The walls are built of concrete and contain several layers of building paper, heavily coated with tar, to make them perfectly water-tight. Having once been thoroughly dried out, the walls have since shown no traces of moisture.

The spectrograph has proved to be an extremely satisfactory instrument. It is of the Littrow or auto-collimating type, and the construction is very simple. A slit, 2 inches (51 mm) long, is mounted at the end of a short tube at the center of the circular iron casting which forms the upper extremity of the instrument. This casting is connected with another iron casting at the bottom of the underground chamber by means of a skeleton steel tube (Fig. 2). The lower cast-

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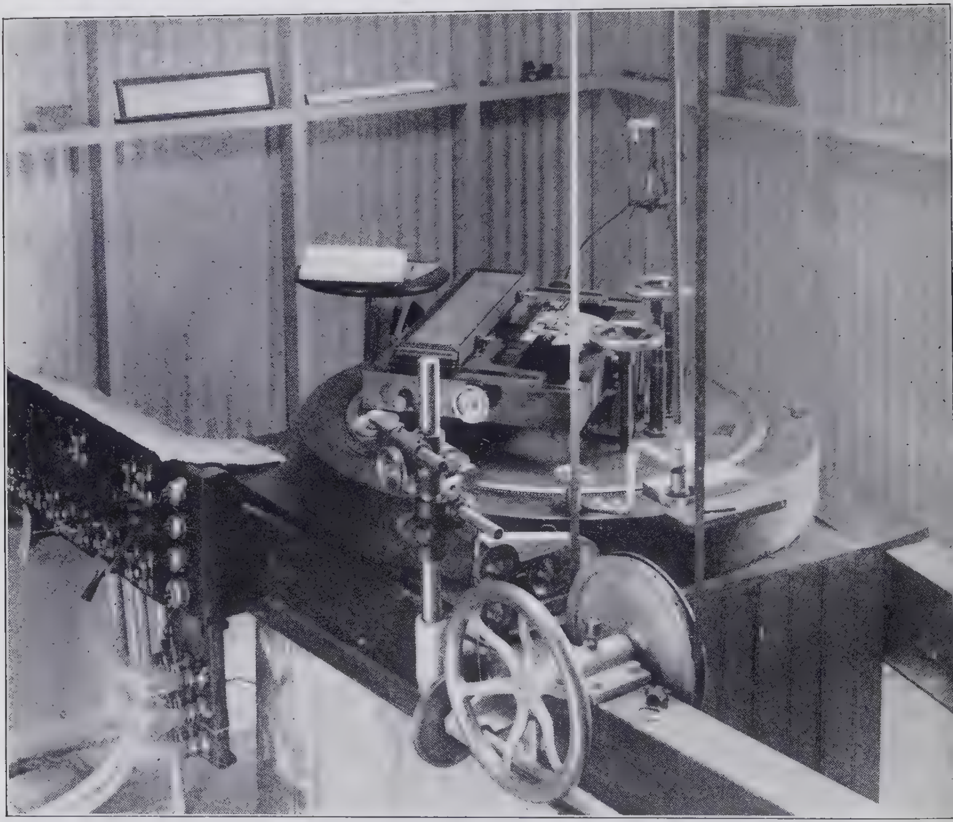
[1] The vertical shaft appears in the drawing and photograph, but many of the details of the connections are not shown.

PLATE XXV



Slit-End of the Thirty-foot Littrow Spectrograph

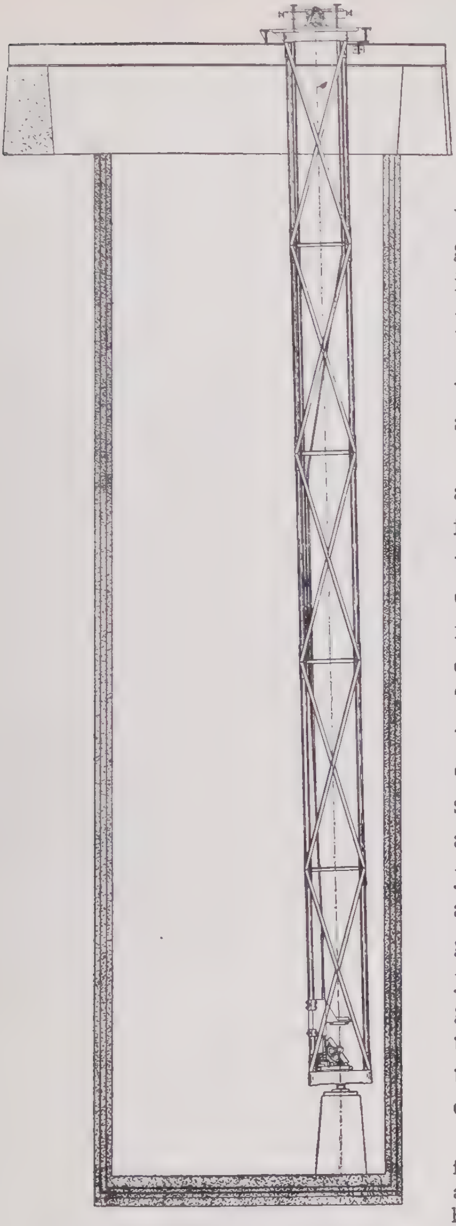


FIG. 2.—Section through underground chamber beneath Tower.

ing terminates in a hemispherical head, which rests on a cast-iron support mounted on a concrete pier. Thus the spectrograph can easily be rotated about a vertical axis,[1] by means of a gear-and-pinion attached to the iron ring which defines the position of the upper casting (Plate XXV). A large divided circle permits the position angle of the slit to be read.

Light from the solar image, after passing through the slit, falls on a 6-inch (15.2 cm) visual objective, by Brashear, of 30 feet (9.1 m) focal length, mounted near the lower end of the skeleton tube (Fig. 2). This lens can be moved vertically for focusing, by means of a rod terminating near the slit. The grating, mounted in a support just below the objective, can also be rotated from above by a similar rod. Scales giving the position of the objective and the angle of the grating can be read with a small telescope from the upper end of the instrument by the aid of electric illumination.

[1] This axis is actually inclined a few degrees from the vertical, to afford space for the 30-foot spectroheliograph, which will occupy a symmetrical position on the east side of the well.

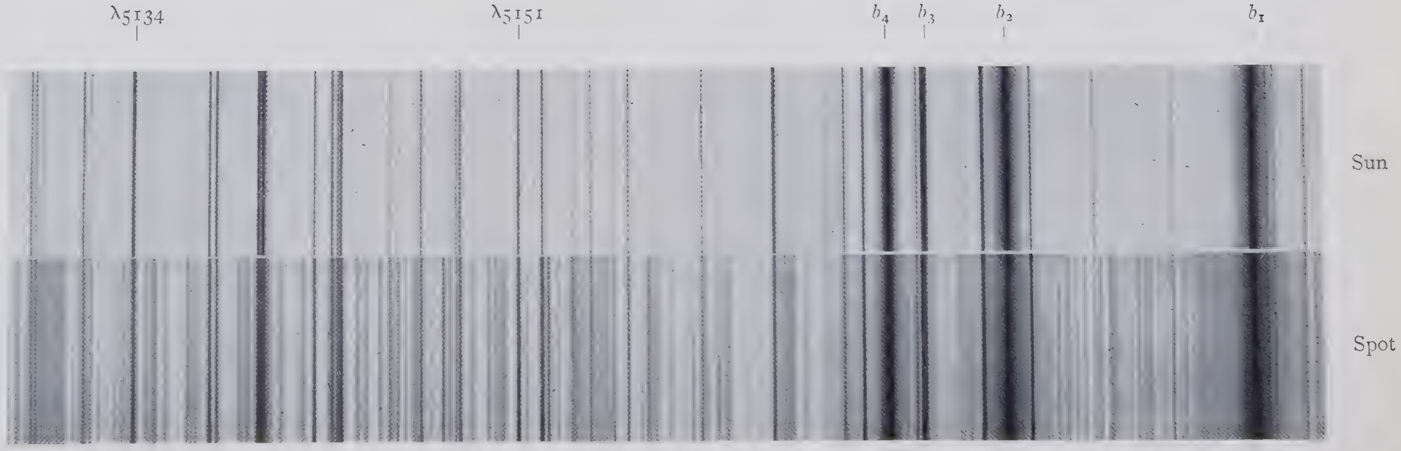
The image of the spectrum is formed on a plate 17 inches (43 cm) long, carried in a plate-holder which can be moved parallel to itself, by rack-and-pinion, so as to permit a large number of narrow spectra to be photographed side by side. The width of the exposed portion of the plate is defined by two adjustable bars, standing a short distance in front of the plate, and independently movable by rack-and-pinion. The plate is shielded from reflected light by a bar placed across the collimating-camera objective. The plate-holder can be inclined so as to make an angle greater than 90° with the incident beam, but with the visual objective employed this is necessary only in the violet.

The spectrograph is furnished with several pieces of auxiliary apparatus, including a device for bringing to the slit light from opposite ends of a solar diameter (employed in spectrographic observations of the solar rotation); a similar device permitting spectra of the center and the limb of the sun (or some point lying between limb and center) to be photographed simultaneously; and a moving plate-holder, with two slits, which permits the spectrograph to be converted into a spectroheliograph.

The first tests of the tower telescope showed that rapid changes of focal length need not be feared. In the Snow telescope these changes are very different on different days, and frequently amount to several inches after the mirrors have been exposed ten minutes to the sun. Moreover, the focal length is increased by such exposure, which would naturally be the case if the heating caused the mirrors to become convex. A considerable part of the effect is doubtless to be attributed to the distortion of the concave mirror, but the change of figure of the two plane mirrors is also an important factor, as is demonstrated by the marked evidences of astigmatism presented by the solar image after continuous exposure of the mirrors. In the case of the tower telescope, when used in the early morning, there is no appreciable change of focal length after the mirrors have been exposed to the sun for about half an hour. Later it appears that the focal length is gradually decreasing, and by noon, after continuous use of the instrument, the change may amount to from four to six inches. In the afternoon the focal length increases, finally returning to the early morning value.

It is evident that the conditions here are very different from those encountered in the case of the Snow telescope. In fact, exposure to

PLATE XXVI



Region of *b* Lines in Spectrum of Sun and Spot
The scale is that of Rowland's Map

sunlight seems to have very little influence on the figure of the mirrors, which continues to change in the manner above outlined even when both mirrors are shielded from the sun. The observed change of focal length must then be due to the change in temperature of the air. With such thick mirrors, the gradual heating of the air during the morning hours would result in expansion of the edges, causing the front and rear surfaces to become concave. This would produce astigmatism which, however, has not yet been noticed before eleven o'clock in the morning, and is not serious until a later hour. Thus the changes in the image are not of such a character as to give serious trouble, since the definition holds well during several hours and the change of focal length is slow enough to permit long exposures to be given. Hence the purpose for which the telescope was built has been accomplished. Nevertheless, the evidence goes to show that the mirrors are thicker than they should be, and for this reason their thickness will probably be reduced as soon as circumstances permit.

The second point to be considered is the quality of the image as affected by the condition of the air about the telescope. To test this, simultaneous observations have been made on several occasions with the Snow and the tower telescopes. In order to make the tests as fair as possible, the aperture of the Snow telescope was stopped down to 12 inches, and the mirrors were exposed to the sun for so short a time as to obviate any such effects of poor definition as would arise from their change of figure. In all cases it has been found that the tower telescope gives a more sharply defined image, the improvement in the "seeing" being from one to two points on a scale of ten. With the Snow telescope, all of the work requiring good definition must be done within a period of about an hour in the early morning or late afternoon. With the tower telescope, the definition is excellent during a much longer period. In fact, except for an interval near noon, this instrument can be kept in active use throughout the day for observations of an exacting nature.

The great focal length of the 30-foot spectrograph has also proved highly advantageous. The only grating available for work in the higher orders is a 4-inch (10.2 cm) Rowland, formerly employed at the Kenwood and Yerkes observatories, and used on Mount Wilson in all of our observations with the 18-foot (5.49 m) Littrow spectrograph. In my experience in photographing sun-spot spectra, which began at the Kenwood Observatory in 1891, I have used this grating in spectrographs of 42½ inches (1.08 m), 7 feet (2.13 m), 18 feet (5.49 m), and 30 feet (9.1 m) focal length. A decided gain has invariably resulted from each increase of focal length, even in the spectra of the third and fourth orders. The grating is not a perfect one, but its definition may be called good. In the 30-foot spectrograph of the tower telescope the ruled surface, being but 53×83 mm, of course receives only a small part of the light from the 6-inch objective, which is completely filled by the solar beam. In spite of the long exposures thus required, our recent photographs of sun-spot spectra, though taken under the unfavorable atmospheric conditions of November and December last, are decidedly superior to those obtained with the 18-foot spectrograph and the Snow telescope during the best observing period last summer, when much larger spots were available. The photographs reproduced in Plate XXVI, on Rowland's scale, were widened with a pendulum apparatus which does not retain the full sharpness of the original negatives. A more perfect device, now under construction, will be used in making the enlargements required for our new map of the spot spectrum. This is to replace the preliminary map, a few copies of which were distributed last year to observers taking part in the co-operative study of sun-spot spectra initiated by the International Solar Union.

The photographs not only show many new spot lines; some of them also bring out for the first time bright reversals similar to those observed visually by Mitchell. Since such reversals may prove of great importance in the interpretation of spot spectra, they will receive careful attention.

Besides serving for the photography of spot spectra by Mr. Adams and myself, the tower telescope has enabled us to continue and extend our comparative study of the spectra of the limb and center of the sun. Moreover, the remarkable results obtained by Mr. Adams in his spectrographic determination of the rotational motion of hydrogen in the sun[1] were derived from photographs made with the 30-foot spectrograph. As for work with the spectroheliograph, I have been confined, pending the completion of the 30-foot instrument, to preliminary experiments with the spectroheliograph attachment of the 30-foot spectrograph. With the aid of a 5-inch grating, which is very bright in the first order, I have secured a few photographs of sun-spot regions with iron and hydrogen lines. These show that a long-focus spectroheliograph of the Littrow form will give excellent results. The use of two camera slits, permitting photographs of the same region to be taken simultaneously with different lines, has been tested and found to be very satisfactory. This method is indispensable for accurate comparisons of the forms and positions of the flocculi of different elements, and will find many applications in our future work.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 24.

FEBRUARY 1908

Contributions from the Mount Wilson Solar Observatory, No. 24
Reprinted from the *Astrophysical Journal*, Vol. XXVII, pp. 213–218, 1908

PRELIMINARY NOTE ON THE ROTATION OF THE SUN AS DETERMINED FROM THE DISPLACEMENTS OF THE HYDROGEN LINES[1]

By WALTER S. ADAMS

In the course of the investigation of the relative displacement of the spectrum lines at the sun's limb, first found by Halm,[2] and confirmed by Professor Hale and myself, a number of plates have been secured including the principal hydrogen lines in the visible spectrum. Since hydrogen extends to a great height in the solar atmosphere, it seems probable that the vapor which contributes to the formation of the hydrogen lines in the solar spectrum lies at a generally higher average level than that giving rise to the greater part of the Fraunhofer lines. Accordingly, if the displacements at the sun's limb are due to pressure, and our results show this almost certainly to be the case, the hydrogen lines might be expected to show smaller displacements than the majority of the lines in the spectrum. To test this question a number of measures upon $H\alpha$ have been made, and the displacements have, in fact, been found to be extremely small, the mean value derived from several plates amounting to less than 0.001 Ångström.

In addition, however, to furnishing results for the pressure-shifts of the hydrogen lines at the sun's limb, the measures of the plates give the displacements due to the rotation of the sun. Since each exposure consists of a spectrum of the limb with a spectrum of the center of the sun on either side for reference, and points on the limb 180° apart are taken alternately, it is evident that if δ is the displacement between center and west limb, for example, and δ' the displacement between center and east limb, both taken regardless of sign,

$$\frac{\delta-\delta'}{2}$$

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 24.

[2] *Astronomische Nachrichten*, 173, 273, 1907.

will be the shift due to pressure, and

$$\frac{\delta+\delta'}{2}$$

will be the shift due to the rotation of the sun. When the values of $\delta+\delta'$ for $H\alpha$ and for the other lines measured were compared, the interesting result was found that in the case of $H\alpha$, $\delta+\delta'$ was considerably larger than for the other lines in its vicinity. Since the plates available were necessarily taken at latitudes on the sun defined by the directions in which the image of the sun could be moved across the slit of the spectrograph, it seemed desirable to continue the work with apparatus which would make it possible to obtain a greater range of latitudes, and accordingly the later plates were taken with the regular rotation attachment employed with the 30-foot spectrograph of the tower telescope. With this instrument any desired position angle on the sun's surface may be brought upon the slit by motion about a vertical axis.

In a previous paper[1] reference was made to the remarkable differences in the behavior of the hydrogen lines at the limb of the sun. It was found that $H\alpha$ was much widened and probably strengthened at the limb as compared with its intensity at the center of the sun, $H\beta$ was similarly affected, though to a less extent, while $H\gamma$ and $H\delta$ were slightly narrowed and weakened. In sun-spots no such exceptions are found, all of the lines being greatly narrowed and reduced in intensity. A few measures upon the widths of $H\alpha$ and $H\gamma$ at center and limb indicate the difference in the behavior of these two lines.

	Width at Center	Width at Limb
$H\alpha$	0.90 Ångström	1.15 Ångström
$H\gamma$	0.46	0.44

The width of $H\alpha$ given in Rowland's table is 0.95 Ångström, the agreement with which is quite satisfactory for measures necessarily as difficult as these.

The plates used in the determinations given here include $H\alpha$, $H\gamma$, and $H\delta$. The nature of the line $H\beta$ is such as to make it practically impossible to use it in work involving accurate measurements. The plates of $H\alpha$ have been made in the second order of the grating, and those of $H\gamma$ and $H\delta$ in the third. In spite of the difference in scale, however, the values given by $H\alpha$ are much the most accurate of the three, owing to the quality of the line. In fact, the values for $H\gamma$ and $H\delta$ are relatively so poor that it is doubtful whether they add appreciably to the accuracy of the mean result. The complicated structure of $H\delta$, owing probably to the presence of foreign lines, is well known, and has given rise to an uncertainty in the value of its wave-length amounting to 0.1 Ångström. The wave-length derived from these measures is 4101.91.

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[1] Hale and Adams, *Contributions from the Solar Observatory*, No. 17; *Astrophysical Journal*, **25**, 300, 1907.

The measures have been made by Miss Lasby of the Computing Division and myself, and are tabulated separately in order to furnish some idea of the degree of accordance attained. It is hardly necessary to call attention to the fact that the accuracy is of quite a different order from that which can be secured with the sharp and narrow lines of the solar spectrum. The difficulties arising from the great width of the lines can, if necessary, be overcome to some extent by the use of broad wires in the measuring microscope, but those due to haziness, complications of structure, and lack of symmetry, are very serious, and give great trouble. Fortunately, the lines between which the displacements are measured are identical in appearance, and the effect of errors of judgment in the estimation of the position of the centers of the lines becomes differential rather than absolute.

In the tables ϕ as usual denotes the latitude, and the velocities given are in kilometers per second. The values are those which are observed directly, before reduction for the earth's motion. The letter L. indicates the measures of Miss Lasby and A. those of the writer.

Plates ω 99, ω 101, and ω 102 contain in some cases two exposures for the same latitude, the mean of which is given in the table. If we

$H\alpha$

ϕ	ω 96		ω 101		ω 102	
	L.	A.	L.	A.	L.	A.
− 0°1........	2.06	2.08	2.07	2.05	2.14	2.09
9.3........			2.01			
14.8........	1.94	2.00	1.96	1.99	2.00	1.99
22.7........	1.88	1.91				
29.6........	1.62	1.71	1.85	1.74	1.76	1.76
44.5........	1.45	1.45	1.51	1.40	1.46	1.46
59.2........	1.05	1.01	0.99	0.95	0.95	1.08
73.4........	0.73	0.66	0.66	0.56	0.70	0.58

$H\gamma$			$H\delta$		
ϕ	ω 99	ω 103	ϕ	ω 99	ω 103
	A.	A.		A.	A.
0°0	2.05	2.06	0°0	2.05	2.07
14.9	1.89	1.94	14.9	1.96	1.98
29.8	1.72	1.65	29.8	1.70	1.74
44.6	1.42	1.40	44.6	1.47	1.38
59.4	1.07	1.11	59.4	1.16	0.99
73.6	0.60	0.66	73.6	0.59	0.58

assign these values double weight, and form means for the separate lines, we obtain the following results:

ϕ	$H\alpha$	$H\gamma$	$H\delta$
	km	km	km
− 0°1	2.09	2.05	2.06
9.3	2.01	....	....
14.8	1.98	1.91	1.97
22.7	1.90	....	....
29.7	1.75	1.70	1.71
44.6	1.46	1.41	1.44
59.3	1.00	1.08	1.10
73.5	0.64	0.63	0.58

There seems to be some tendency for $H\alpha$ to give values larger than those furnished by the other two lines, and a result of this sort would seem to be by no means impossible in view of the marked difference in its behavior as regards width and intensity. Until additional material, however, is available, particularly for $H\gamma$ and $H\delta$, it is hardly justifiable to consider this difference in velocity as real, or to draw conclusions from it.

The result of forming a general mean of all the observations is given in the table below. The column $v+v_1$ gives the linear velocity corrected for the earth's motion, and ξ as usual denotes the angular velocity. The period in days corresponding to the angular velocity is given in the succeeding column. It is evident that the points at latitudes 9°3 and 22°7 are of very low weight, the first being based upon only a single measure, and the second upon but two. The last two columns give the values of the angular velocity and the period for the reversing layer, and are taken from an earlier paper on the rotation of the sun.[1]

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[1] Adams, *Contributions from the Solar Observatory*, No. 20; *Astrophysical Journal*, **26**, 203–224, 1907.

ϕ	v	$v+v_1$	ξ	Period	ξ'	Period
	km	km	km	days		days
− 0°.1	2.07	2.21	15°.7	22.9	14°.7	24.5
9.3	2.01	2.15	15.5	23.2	14.5	24.8
14.8	1.96	2.10	15.4	23.4	14.4	25.9
22.7	1.90	2.03	15.6	23.1	13.9	25.9
29.7	1.73	1.87	15.3	23.5	13.7	26.3
44.5	1.44	1.55	15.4	23.4	12.8	28.1
59.3	1.04	1.12	15.6	23.1	12.2	29.5
73.5	0.63	0.67	16.7	21.6	11.8	30.5

Two important conclusions are at once evident from an examination of these results. The first is that the rotational velocity of the hydrogen gas is decidedly higher than that of the general reversing layer, amounting at the equator to 1° in the angular motion. A result of this kind was perhaps to be expected in view of the differences found among the different lines studied in the previous investigation.[1] It was there shown that lines due to lanthanum and cyanogen, both of which are known to lie at a low level in the solar atmosphere, gave consistently small values for the rotational velocity, although the difference was slight. Similarly, two or three other lines gave systematically large values. The conclusion seems to be unavoidable that what we may call the "effective" level of the vapors, the integrated action of which gives rise to the hydrogen lines at the sun's limb, lies very high in the sun's atmosphere, and that at this higher level the angular velocity is considerably greater than in the region close to the photosphere.

A second conclusion to be drawn from these results is also of great importance. It is that at the level of the hydrogen gas at which the spectrum lines are formed the law of the sun's equatorial acceleration has ceased to hold. An examination of the table shows that the values of ξ for the various latitudes, with the possible exception of 73°.5, are constant to within less than might perhaps have been expected from the internal agreement of the measures. Even at the highest latitude the value of the angular velocity is so sensitive to a slight difference in linear velocity that the discordance in the value of ξ is by no means excessive. In fact, a difference in the value of $v+v_1$ of less than 0.05 km would be sufficient to bring the value of ξ into agreement with the results for the other latitudes, and such an error would not be at all abnormal in determinations of this sort.

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[1] Adams, *loc. cit.*

The rather fundamental character of these results will, of course, lead to a continuation of the investigation, and to an extension of the measures to include lines of other elements, particularly sodium, and, if possible, calcium. In some such way it would seem not improbable that an upper limit may be set to the region within which the law of the sun's equatorial acceleration continues to hold.

MOUNT WILSON, CALIFORNIA
February 1908

Contributions from the Mount Wilson Solar Observatory, No. 25
Reprinted from the *Astrophysical Journal*, Vol. XXVII, pp. 219–229, 1908

PRELIMINARY NOTE ON THE ROTATION OF THE SUN AS DETERMINED FROM THE MOTIONS OF THE HYDROGEN FLOCCULI[1]

By GEORGE E. HALE

The first photographs of the hydrogen flocculi were taken with the Rumford spectroheliograph of the Yerkes Observatory in May 1903. Several reproductions of negatives obtained during that year, accompanied by a brief discussion of the nature of the flocculi, were published in a paper on the Rumford spectroheliograph by Mr. Ellerman and myself.[2] With the instrument employed, it was then possible to photograph only comparatively narrow zones of the solar image by hydrogen light. For this reason the study of the hydrogen flocculi was necessarily confined to their physical nature and their relationship to other solar phenomena.

The completion of the Snow telescope and the 5-foot spectroheliograph made it possible to include systematic records of the hydrogen and iron flocculi, in addition to those of calcium, in the daily series of photographs commenced on Mount Wilson in October 1905. Since the entire solar image is shown in all photographs of this series, the negatives are suitable for the determination of the heliographic positions and daily motions of the hydrogen flocculi. Two heavy flint-glass (Schott No. 0.102) prisms, each of 63° 29′ angle, are employed in the spectroheliograph, with collimator and camera objectives of 5 feet (152 cm) focal length, giving sufficient dispersion to permit good photographs to be made with the $H\delta$ line. On account of the demands of the routine work, comparative studies of the hydrogen flocculi with the $H\alpha$, $H\beta$, and $H\gamma$ lines were postponed until the 30-foot spectroheliograph of the tower telescope could be applied to this purpose.

The material available for the determination of the motions of the hydrogen flocculi comprises a large collection of photographs, covering the period from October 1903 to the present date. On every clear day hydrogen photographs are made both in the early morning and the late afternoon. It is fortunate for the present purpose that no greater time-interval separates the successive plates, since the rapid changes in form of the hydrogen flocculi make the identification of objects for measurement the most difficult part of the investigation. These rapid changes are associated with proper motions much larger than those observed in the case of the calcium flocculi. It was partly for this reason that a systematic study of the hydrogen flocculi was deferred until the completion of an extensive investigation of the calcium plates. The difficulties of identification and measurement offered by the calcium flocculi, while much less serious, afford just the practice required in preparation for work on the hydrogen plates.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 25.

[2] *Publications of the Yerkes Observatory*, Vol. III, Part 1.

A few identifications and measurements of hydrogen flocculi were nevertheless made in order to test the available material, and to ascertain its fitness for work on the solar rotation. This preliminary examination of the plates left no doubt as to the rapid changes of form and the large proper motions peculiar to the hydrogen flocculi. It also indicated that the rotational velocities, at least in the higher latitudes, would probably be greater than in the case of the calcium flocculi.

After Mr. Adams' recent spectrographic work had shown the high equatorial velocity of hydrogen, as determined by the relative displacement of lines observed at points very near the east and west limbs of the sun, it became a matter of great interest to continue, along two entirely independent lines, the investigation of the rotational motion of this gas. Accordingly, Mr. Adams extended his observations to higher latitudes, with the extremely interesting results given in another paper.[1] At the same time Miss Ware undertook the measurement, with the heliomicrometer, of a sufficient number of hydrogen plates to afford a preliminary determination of the motions of the flocculi. Although a much more extensive study will be required to give definitive results, there seems to be no doubt that the motions of the hydrogen flocculi differ appreciably from those of the calcium flocculi, and indicate the operation of a different law of rotation.

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[1] Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 24, *Astrophysical Journal*, 27, 213, 1908.

The results given below were derived from 547 measures of hydrogen flocculi on 20 different plates, the numbers and dates of which are given in Table I. The intervals separating the successive plates varied from 10 to 14.5 hours. In the case of three photographs (Nos. 1080, 1086, and 1090), taken within an interval of about twenty-four hours, two of the plates showed the presence of systematic errors, the latitudes of corresponding points differing by amounts which increased regularly from the equator toward the north pole, and decreased in the same regular manner toward the south pole. As it was evident that the effect must be due to errors in the orientation of the plates, values for the orientation, differing 1.0 and 1.5 respectively from the calculated values, were assumed. The magnitudes of these corrections were so chosen as to eliminate the observed systematic deviations in latitude. In applying these corrections, no attention was paid to their effect upon the longitudes. If we omit the measures of the flocculi secured with the aid of these plates we obtain the values of ξ' given in the fourth column of the table.[1]

TABLE I

Plate No.	Date	Plate No.	Date	Plate No.	Date
	1906		1906		1906
507	July 1, 6:55 A. M.	867	Aug. 24, 6:43 A. M.	1086	Sept. 21, 4:38 P. M.
510	July 1, 5:30 P. M.	868	Aug. 24, 5:16 P. M.	1090	Sept. 22, 7:14 A. M.
514	July 2, 6:40 A. M.	874	Aug. 25, 6:36 A. M.		1907
516	July 2, 5:37 P. M.	881	Aug. 26, 6:59 A. M.	2392	July 30, 7:08 A. M.
519	July 3, 6:38 A. M.	885	Aug. 26, 5:24 P. M.	2396	July 30, 5:46 P. M.
854	Aug. 23, 6:28 A. M.	1075	Sept. 20, 4:47 P. M.	2429	Aug. 3, 6:37 A. M.
861	Aug. 23, 5:16 P. M.	1080	Sept. 21, 6:53 A. M.	2433	Aug. 3, 5:36 P. M.

Table II gives the number of measures of hydrogen flocculi in five-degree zones, and the mean angular rotations, ξ, reduced from synodic to sidereal values. The means combine the results for corresponding zones in the northern and southern hemispheres. The

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[1] The orientation of spectroheliograph plates made with the Snow telescope is determined by the aid of test plates, on which the solar image is photographed several times after being allowed to drift a certain distance between successive exposures. These test plates are made for various settings of the coelostat (east and west) and second mirror (north and south), the positions being determined by the aid of scales provided for the purpose. It has occasionally happened, as in the present instance, that a test plate, for the particular settings of the two plane mirrors, was not made within a sufficiently short interval of the actual time of observation, thus introducing such an error of orientation as that mentioned above.

TABLE II

Zone	Hydrogen ($H\delta$)			Calcium (H_2)		
	No. of Measures	ξ	ξ'	No. of Measures	ξ	ξ''
0°± 5°	91	14°.3	14°.4	232	14°.5	14°.5
± 5 ±10	77	14.4	14.6	262	14.3	14.3
±10 ±15	95	14.6	14.7	317	14.3	14.3
±15 ±20	73	14.5	14.5	326	14.2	14.2
±20 ±25	71	14.7	14.7	259	14.2	14.2
±25 ±30	65	14.7	14.6	153	14.0	14.1
±30 ±35	33	14.9	15.0	99	13.8	13.8
±35 ±40	23	14.6	15.0	26	14.0	13.9
±40 ±45	19	14.4	14.3	6	13.2	13.2

fourth column (ξ') has already been explained. In the next two columns are given, for comparison, the number of measures in each zone and the values of ξ derived from the measurement of 1,680 calcium (H_2) flocculi on 51 negatives taken with the Snow telescope and 5-foot spectroheliograph, during the period June 18–September 22, 1906. These are the preliminary results of a study of the motions of the calcium flocculi, which involves the measurement of about 30 more plates, now nearly completed by Miss Ware. The last column, ξ'', contains the results for calcium obtained with the same number of measures used for hydrogen (except in the zone 40°–45°, where only 6 measures were available). The internal agreement of the measures indicates that these means for the calcium flocculi are, in general, about twice as precise as those for the hydrogen flocculi.

All of the work of measurement has been done with the heliomicrometer.[1] In the case of calcium, settings are made with the cross-hairs on flocculi previously identified by comparison with the preceding or following plate. The hydrogen flocculi offer greater difficulties, not only because of their rapid changes, but also because of their small contrast on the photographs. Two negatives are compared in the Zeiss stereocomparator, with the aid of the monocular attachment. Great pains are taken in making the identifications, all doubtful cases being rejected. Small nuclei, which are rather darker than the average flocculi, seem to be the most persistent objects, and are usually selected for measurement. These are marked on the glass

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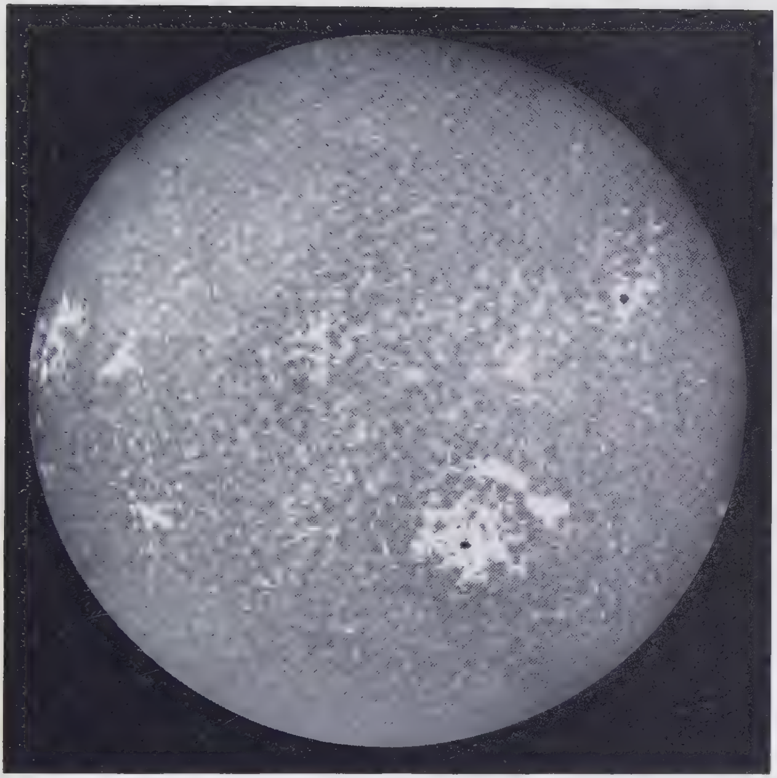
[1] Hale, *Contributions from the Solar Observatory*, No. 16; *Astrophysical Journal*, **25**, 293, 1907.

PLATE XXVII



THE SUN, SHOWING THE CALCIUM (H_2) FLOCCULI
1906, August 25, 6^h 18^m A. M., Pacific Standard Time

side of the negative with dots of ink, and the positions of these dots are measured with the heliomicrometer. The flocculi themselves are too faint for measurement, and the errors due to large proper motions are far greater than any which can arise from this procedure.

In the case of the calcium flocculi the existence of the equatorial acceleration is clearly evident. The hydrogen flocculi, however, show no systematic variation of ξ with the latitude. As already remarked, the hydrogen measures are less reliable than those of calcium, because of the inclusion of a much smaller number of flocculi, larger proper motions, and more rapid changes of form. We may therefore take the mean value of ξ for all the zones (14°6) as a provisional determination of the daily angular motion of the hydrogen flocculi.

The provisional results here given for the motions of the hydrogen flocculi, though of rather low weight, are of importance when taken in connection with Mr. Adams' spectrographic determinations.[1] Both methods agree in showing that the hydrogen in the sun does not share the equatorial acceleration observed in the case of sun-spots, faculae, calcium flocculi, and reversing layer. The simplest way to account for this difference is on the assumption that the hydrogen whose motion is measured lies at a higher level. As this raises the question of the nature of the flocculi and their levels as compared with those of the spots and faculae, it may be advantageous to review briefly the evidence afforded by existing observations, and to mention some of the observations required to clear up obscurities.

Let us first consider the calcium flocculi photographed with the spectroheliograph when the camera slit is set on one of the bright lines H_2 or K_2 (Plate XXVII). With radial slit these bright lines project at the limb well into the chromosphere, retain considerable width for a few thousand miles, and then narrow down to the width of H_3 and K_3. Since H_2 flocculi frequently cover sun-spots, and are sometimes photographed as projections at the sun's limb, we may safely say that their average level is that of the lower chromosphere. The photometric measurement of the relative intensities of H_2 flocculi and the adjoining photosphere, at various distances from the limb, should assist in defining their level more closely.

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[1] *Loc. cit.*

When the camera slit of a spectroheliograph is set on H_1 or K_1, bright regions, smaller in area and finer in detail than the H_2 flocculi, appear on all parts of the solar disk (Plate XXVIII). The forms of these H_1 flocculi agree closely with those of the faculae in direct photographs of the sun, and it is still uncertain in what relative degree the continuous spectrum of the faculae and the light of the low-lying dense calcium vapor contribute toward their formation. To settle the question the following methods may be used: (1) Comparisons of the forms and positions of H_1 flocculi and faculae, photographed simultaneously with a spectroheliograph having two camera slits; (2) Photometric determinations of the intensity-curves of H_1 and K_1 in photographs of the spectra of faculae and the adjoining photosphere; (3) Photometric measurements, on spectroheliograph plates, of the relative intensity of faculae and H_1 flocculi at various distances from the limb.

Pending further work on this subject, we need have little hesitation in ascribing to the H_1 flocculi a level coinciding with or slightly above that of the faculae, and below that of the H_2 flocculi.

As for hydrogen, the reasons which led to the belief that its dark flocculi represent, on the average, a relatively high level, are given in the paper already mentioned.[1] Since that time the accumulation of evidence has only tended to strengthen this belief. It has been found, for example, in comparing the relative distances from the sun's limb of corresponding calcium and hydrogen flocculi, that the latter are, in general, displaced toward the limb by a very appreciable amount. The displacements vary greatly for different flocculi, but the average difference of level represented may be roughly stated as from one to two thousand miles. On account of the effect of atmospheric disturbances, however, an accurate determination of this difference of level cannot be made until photographs taken simultaneously with H_2 and one of the hydrogen lines become available.

In addition to the direct evidence afforded by these displacements, we have other evidence which also seems significant. It was found at the Yerkes Observatory that exceptionally dark hydrogen flocculi are frequently represented on calcium (H_2) plates by dark objects, roughly corresponding with them in form. Our Mount Wilson

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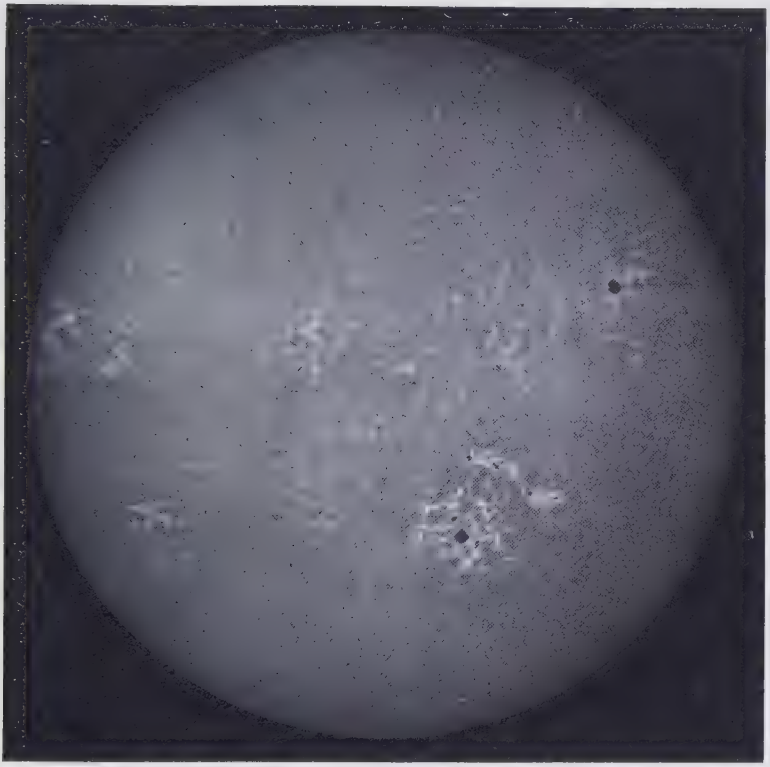
[1] *The Rumford Spectroheliograph of the Yerkes Observatory*, p. 20.

PLATE XXVIII



THE SUN, SHOWING THE CALCIUM (H_1) FLOCCULI
1906, August 25, $6^h\ 22^m$ A. M., Pacific Standard Time

records show a great number of these dark calcium flocculi, which appear to be invariably associated with exceptionally dark hydrogen flocculi. Mr. Ellerman has photographed the spectra of these objects and found that the marked strengthening and widening of their hydrogen lines is accompanied by a similar strengthening and widening of H_3 and K_3. This indicates that these hydrogen flocculi are at the H_3 level, rather than in the lower region of denser calcium vapor represented by H_2. When describing the work of the Kodaikanal Observatory before the Royal Astronomical Society, Mr. Michie Smith stated that these dark calcium flocculi, when photographed near the limb, are found to agree in position with prominences. This is in harmony with similar results obtained at the Yerkes Observatory, and leaves little room for doubt that some of the dark hydrogen flocculi are prominences photographed in projection on the solar disk. It is probable, however, that the less conspicuous dark hydrogen flocculi occupy a lower level, at or somewhat below the upper part of the chromosphere.[1] Thus the assumption that the dark hydrogen flocculi are high-level phenomena (as compared with the H_2 calcium flocculi), which was at first made simply to account for their darkness, on the ground that absorption effects would be most likely to present themselves in the higher and cooler gases, seems to be borne out by the evidence just cited.

The results obtained from the study of the rotational velocity of the hydrogen flocculi may now be considered in this connection. If these flocculi, on the average, are at a higher level than the H_2 calcium flocculi, the difficulty of ascribing to them a different rate and law of rotation is greatly decreased. In Wilsing's theoretical discussion of the law of the solar rotation,[2] the important effect of internal friction is given special consideration. On account of this friction, Wilsing assumes that the differences of angular velocity "must diminish as the center of the sun is approached, until a surface is reached, the particles of which rotate with sensibly constant angular velocity about a common axis." Above the photosphere there may be considerable internal friction at the base of the chromosphere, but this friction must decrease rapidly in going outward. Finally, Wilsing assumes, a spherical surface will be reached which, like the inner one, rotates with uniform velocity.

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[1] It is of course supposed that the hydrogen extends down to the base of the chromosphere, but that the region of effective absorption, represented by the dark flocculi on the spectroheliograph plates, is at the level mentioned.

[2] *Astrophysical Journal*, 23, 247, 1906.

Through the effect of friction the different rotational velocities observed by Mr. Adams in the case of lines of different elements find ready explanation.[1] Carbon and lanthanum, which give values for the daily rate about $0^\circ.1$ less than the mean result for all the lines employed, are elements which lie at a low level in the solar atmosphere. We now find that the dark hydrogen flocculi, to which a high level in the chromosphere has been independently ascribed, show no evidence of equatorial acceleration.

Table III brings together the results of various determinations of the solar rotation, as indicated by the motions of sun-spots, faculae, reversing layer, calcium and hydrogen flocculi, and hydrogen. Carrington's spot values are taken from his *Observations of the Spots on the Sun*. Spoerer's are computed from his formula

$$\xi = 8^\circ.548 + 5^\circ.798 \cos b$$

where b is the latitude.[2] Maunder's values of ξ are derived from his formula

$$\xi = 866'.6 \pm 128' \sin^2 \lambda$$

where λ is the latitude.[3] The results given for the faculae are due to Stratonoff,[4] while those for the calcium flocculi include the Kenwood spectroheliograph results,[5] Mr. Fox's Rumford spectroheliograph results for 1903–4,[6] and the Mount Wilson results for 1906 (Table II). The values for the reversing layer are those of Mr. Adams.[7] For the hydrogen flocculi and for hydrogen (spectrographic),[8] mean

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[1] *Contributions from the Solar Observatory*, No. 20, p. 13; *Astrophysical Journal*, **26**, 247, 1907.

[2] *Potsdam Publications*, Vol. X, Part 1.

[3] *Monthly Notices*, **65**, 823, 1905.

[4] *Mem. Acad. de St. Pétersbourg*, Vol. V, No. 11.

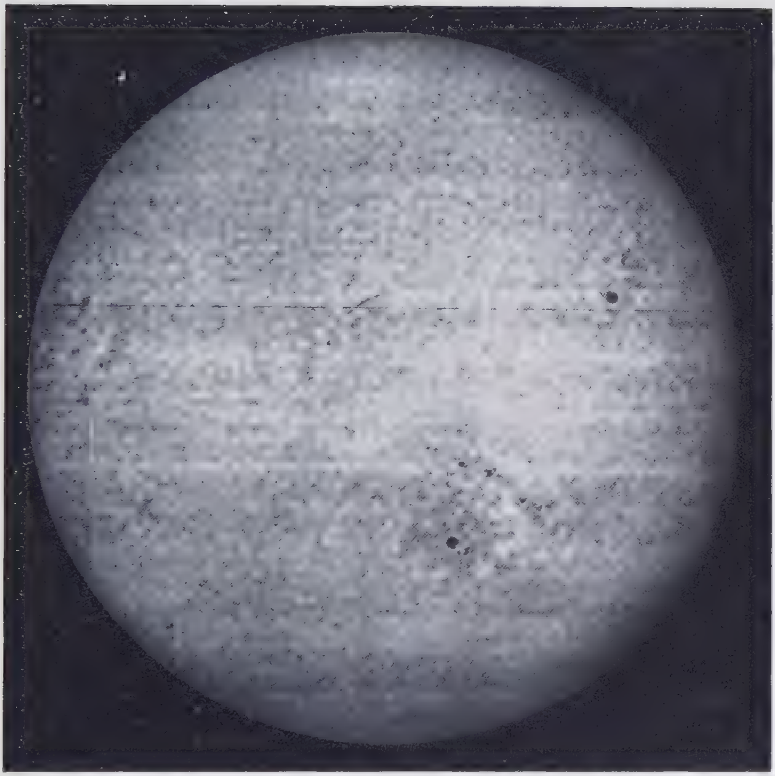
[5] Hale and Fox, *The Rotation of the Sun, as Determined from the Motions of the Calcium Flocculi* (in press).

[6] *Science*, April 19, 1907.

[7] *Loc. cit.*

[8] Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 24; *Astrophysical Journal*, **27**, 213, 1908.

PLATE XXIX



THE SUN, SHOWING THE HYDROGEN ($H\delta$) FLOCCULI
1906, August 25, 6^h 36^m A. M., Pacific Standard Time

TABLE III

	Spots				Faculae Stratonoff	Reversing Layer Adams	Calcium Flocculi (H_2)				Hydrogen Flocculi ($H\delta$)	Hydrogen (Spectrographic)
	Carrington	Spoerer	Maunder	Unweighted Means			Kenwood	Fox 1903–4	Mount Wilson	Unweighted Means		
0°± 5°.......	14°.42	14°.34	14°.44	14°.40	14°.62	14°.70	14°.66	14°.49	14°.46	14°.54	14°.6	15°.5
± 5°±10°.......	14.35	14.30	14.41	14.35	14.61	14.58	14.52	14.42	14.30	14.41		
±10°±15°.......	14.21	14.21	14.34	14.25	14.31	14.43	14.37	14.24	14.30	14.30		
±15°±20°.......	14.06	14.08	14.25	14.13	14.18	14.23	14.22	13.94	14.22	14.13		
±20°±25°.......	13.90	13.90	14.13	13.98	14.19	14.00	14.12	13.67	14.19	13.99		
±25°±30°.......	13.73	13.69	13.99	13.80	14.08	13.72	13.90	13.96	14.04	13.97		
±30°±35°.......	13.54	13.44	13.83	13.60	13.60	13.43	13.76	13.70	13.80	13.75		

velocities, including all the results obtained within 40° of the equator, are taken as most representative.[1]

The results show no such difference between the rotational velocities of spots and calcium flocculi as the higher level of the latter would lead us to expect. The large values of ξ for the faculae are not easily explained, but the difficulties involved in their measurement necessarily render them somewhat uncertain. The high spectrographic velocities of the reversing layer and of the hydrogen above it arouse the suspicion that the spots, faculae, and flocculi do not move as rapidly as the gaseous medium in which they float, possibly because they retain the velocities of lower levels, from which the faculae and flocculi, if not the spots, may rise. The great speed of hydrogen may be due, however, to the fact that the gas most effective in the production of the hydrogen lines at the limb lies at a level above that of the hydrogen flocculi.[2] In the hope of clearing this up spectrographic observations will be made at points on the disk within the region where the motions of the hydrogen flocculi have been measured.

The importance of improving and extending the above results calls for more work of a varied character. A vigorous attempt should be made to determine the level of sun-spots, by the spectroheliograph method suggested elsewhere[3] or by other means. Extensive observations of the faculae are especially needed, as the difficulty of securing accurate measures of objects photographed only in the neighborhood of the limb must be recognized. This work can be most usefully supplemented by an investigation of the motions of the H_1 flocculi, particularly if the above-mentioned methods of testing their relationship to the faculae are put into practice. The spectrographic observations should be extended to other lines, special attention being devoted to hydrogen, calcium, sodium, and magnesium. Observers with spectroheliographs are strongly urged to adapt their instruments for the photography of the hydrogen flocculi, as many measurements of these objects are required. Indeed, the interpretation of the phenomena presented by these flocculi, other than those connected with their rotation, offers in itself a large field for research.

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[1] In a future paper certain data not now available, including the latest spectrographic results of Dunér and Halm and additional observations of the calcium flocculi by Fox, will be used in a general discussion of the solar rotation.

[2] As $H\alpha$ seems to give higher spectrographic velocities than $H\gamma$ and $H\delta$, besides being greatly strengthened (while the others are almost unchanged) at the limb, some of the difference may possibly be due to this cause.

[3] *Report of the Director of the Mount Wilson Solar Observatory, for the Year Ending September 30, 1907.*

Since anomalous dispersion phenomena might be expected to arise under just such conditions as are here assumed to obtain in the flocculi, the possibility of their existence must not be ignored. It is hoped that investigations now in progress here will throw some light on this fundamentally important question.

Mount Wilson Solar Observatory
February 1908

Contributions from the Mount Wilson Solar Observatory, No. 26
Preprinted from the *Astrophysical Journal*, Vol. XXVIII (September), 1908

SOLAR VORTICES

BY GEORGE E. HALE

The problem of interpreting the complex solar phenomena recorded by the spectroheliograph has occupied my attention since the first work with this instrument in 1892. The measurement of the daily motions in longitude of the calcium flocculi has led to several new determinations of the solar rotation,[1] and their areas, measured by a photometric method, are being used as an index to the solar activity. Various investigations on their forms at different levels,[2] their distribution in latitude and longitude, etc., have also been carried out. But the failure of the calcium flocculi to indicate the existence of definite currents in the solar atmosphere has been a disappointment.

The hydrogen flocculi, though occupying the same general regions on the sun's disk, are distinguished from those of calcium by several striking peculiarities. In the first place, most of them are dark, while the corresponding calcium (H_2) flocculi are bright. Secondly, as I have recently shown,[3] they seem to obey a different law of rotation, in which the equatorial acceleration (better, the polar retardation), shared by the spots, faculae, and calcium flocculi, does not appear. A third peculiarity, briefly mentioned in previous papers, is clearly visible on many hydrogen photographs. It is a decided definiteness of structure, indicated by radial or curving lines, or by some such distribution of the minor flocculi as iron filings present in a magnetic field (see, for example, *Astrophysical Journal*, Vol. XIX, Plates X and XII). First recognized at the beginning of our work with the hydrogen lines in 1903, this suggestive structure has repeatedly shown itself on the Mount Wilson negatives. But its true meaning did not appear until the results described in this paper had been obtained.

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[1] Hale and Fox, *The Rotation of the Sun, as Determined from the Motions of the Calcium Flocculi.* Carnegie Institution (in press); Fox, *Science*, April 19, 1907; Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, **27**, 219, 1908.

[2] Hale and Ellerman, *Publications of the Yerkes Observatory*, Vol. III, Part I.

[3] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, **27**, 219, 1908.

With the Rumford spectroheliograph the hydrogen lines $H\beta$, $H\gamma$, and $H\delta$ were used. Certain differences between the photographs, which seemed to depend upon the wave-length, pointed to the desirability of trying $H\alpha$. But plates sufficiently sensitive to red light were not to be had at that time, and therefore the experiment was postponed.

The extreme sensitiveness in the red of plates prepared according to a formula due to Wallace[1] now renders it a simple matter to photograph the sun with $H\alpha$. Some preliminary work with the spectroheliograph attachment of the 30-foot Littrow spectrograph of the tower telescope, in which I had the assistance of Mr. Adams, indicated that bright flocculi are more numerous and extensive when photographed with $H\alpha$ than when $H\delta$ is used. I then tried $H\alpha$ with the five-foot spectroheliograph of the Snow telescope, and immediately obtained excellent results. The images were stronger and of much better contrast than those given by $H\delta$. Moreover, the curved and radial structure surrounding sun-spots was so striking as to lead to the hope that important advances might be expected to follow from the systematic use of the $H\alpha$ line.

On account of the difference in curvature of $H\alpha$ and $H\delta$, these preliminary photographs made with $H\delta$ slits showed only a very narrow zone of the solar image. A new pair of slits, of suitable curvature for $H\alpha$, was accordingly made for the five-foot spectroheliograph, and as soon as these were ready I completed the adjustments of the instrument, with Mr. Ellerman's assistance, and made comparative photographs of the entire disk with $H\alpha$ and $H\delta$. The differences exhibited by these plates are very marked. For example, a long dark flocculus, strongly shown by $H\alpha$, is represented on an $H\delta$ photograph by only a few of its most intense parts. In the case of bright flocculi, the differences are even more conspicuous, large luminous areas shown by $H\alpha$ being absent from the $H\delta$ plates. To eliminate errors arising from possible changes on the sun between exposures, the photographs were taken in rapid succession, an $H\alpha$ plate between two of $H\delta$. In this way all doubts as to the genuine-

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[1] *Astrophysical Journal*, 26, 299, 1907.

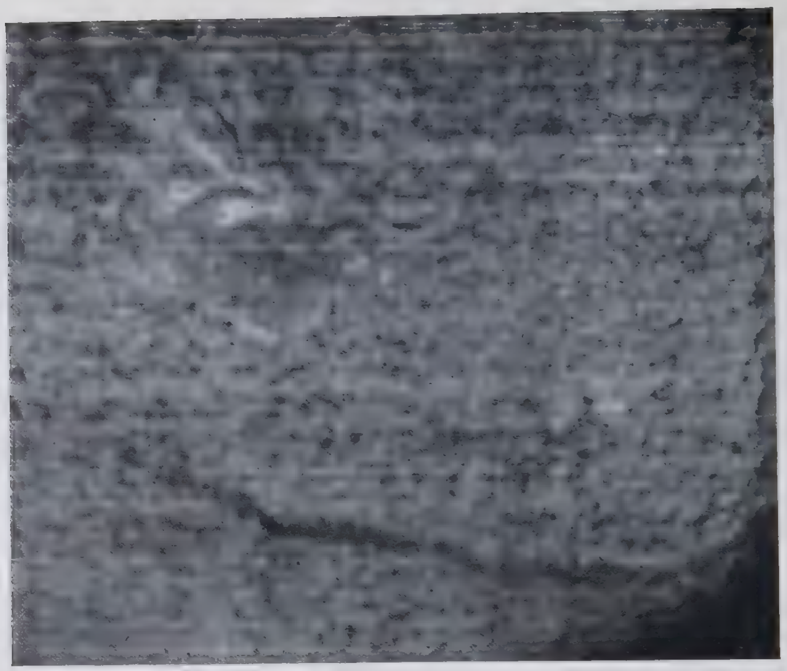


FIG. 1.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\alpha$ LINE
1908, May 1, $4^h\ 48^m$ P. M. Scale: Sun's Diameter = 0.2 Meter

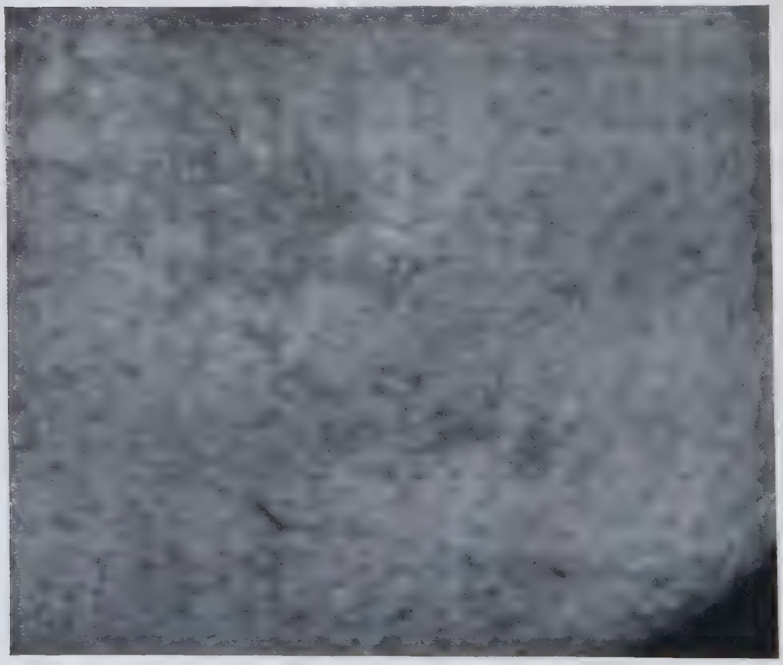


FIG. 2.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\delta$ LINE
1908, May 1, $5^h\ 07^m$ P. M. Scale: Sun's Diameter = 0.2 Meter

PLATE XXXI

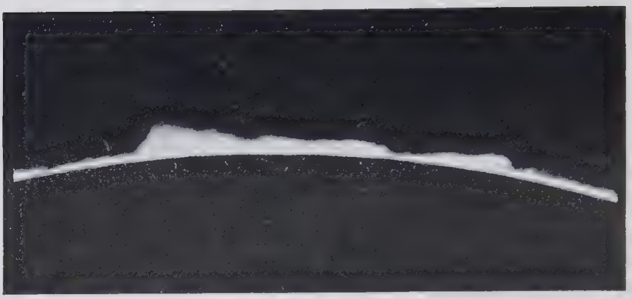
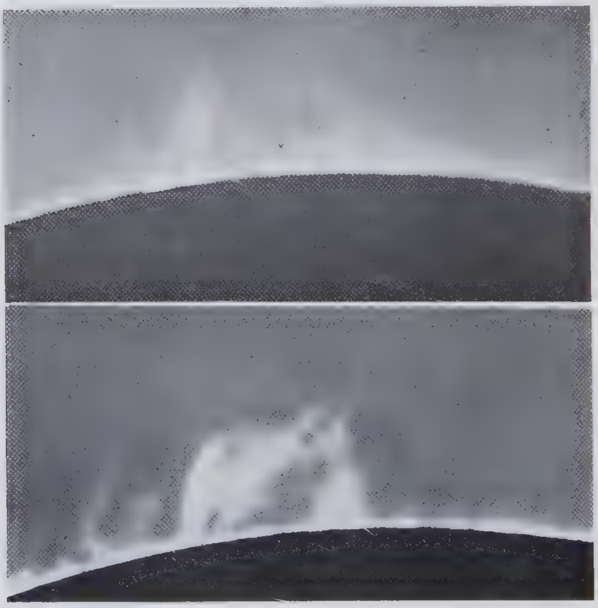


FIG. 1.—PROMINENCES AT EASTERN LIMB OF THE SUN
1908, May 26, $6^h\ 38^m$ A. M. Scale: Sun's Diameter = 0.3 Mete.



FIGS. 2 AND 3.—PROMINENCES PHOTOGRAPHED WITH $H\delta$ (FIG. 2) AND $H\alpha$ (FIG. 3)
1908, April 3. Scale: Sun's Diameter = 0.3 Meter

ness of the observed differences were removed. Plate XXX illustrates the general character of these differences, concerning the cause of which we may now inquire.

It naturally occurred to me that photographs of a prominence at the sun's limb, taken with the various hydrogen lines, would be likely to throw light on the question. Mr. Ellerman accordingly made a series of photographs of a prominence, using the lines $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$. The fall of intensity toward the violet was very marked, the faint $H\delta$ image bringing out only the brightest parts of the prominence as photographed with $H\alpha$ (Figs. 2 and 3, Plate XXXI). $H\beta$ and $H\gamma$ gave intermediate results, resembling those obtained with $H\delta$.

It thus seems probable that the marked intensity of the $H\alpha$ flocculi results from the great strength of the $H\alpha$ line in the chromosphere and prominences. $H\delta$ is strong enough in the middle and sometimes in the upper chromosphere and in the lower parts of bright prominences to show the hydrogen in these regions when projected on the disk. $H\alpha$, being much more intense, renders visible a higher region of the solar atmosphere, including the upper chromosphere and bright prominences. Whether these are to appear as bright or dark flocculi, when photographed against the disk, probably depends primarily upon their temperature, though the conditions may not be such as to permit the direct application of Kirchhoff's law.

But the photographs bring out a second fact of interest. Although, as has been stated, the flocculi are generally stronger on the $H\alpha$ plates, it cannot be said that these $H\alpha$ images are merely intensified $H\delta$ images. For there is an important point of difference: dark $H\delta$ flocculi are sometimes replaced on the $H\alpha$ plates by bright flocculi or by apparently neutral spaces. The condition of the hydrogen in such regions thus appears to be the same as in certain stars, whose spectra show $H\alpha$ bright and the more refrangible hydrogen lines dark.[1]

The importance of continuing the work of photographing the sun with $H\alpha$ was obvious, and I immediately modified the daily programme of observations with this object in view. In the photography of the chromosphere and prominences at the limb, $H\alpha$ was substituted for the H line of calcium, since it was found to give stronger and sharper negatives. For the disk $H\alpha$ was adopted in place of $H\delta$, though work was continued with the latter line long enough to secure a series of comparative photographs. Later, as more $H\alpha$ plates were needed, the daily series of photographs with the iron line λ 4046 was discontinued, and all of the observing time of the Snow telescope in the morning devoted to $H\alpha$ work.[1] In the afternoon this line is also used most of the time, though one plate is made with H_1 and one with H_2 of calcium.

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[1] I leave for future consideration the question whether the neutral regions on the $H\alpha$ plates are to be regarded as bright flocculi of reduced intensity. It will also be important to determine whether Kayser's explanation of the appearance in a stellar spectrum of both bright and dark hydrogen lines (*Astrophysical Journal*, 14, 313) will apply to solar phenomena.

A serious difficulty at once presented itself. Previously only a few photographs had been taken during each of the best observing periods, which last less than two hours in the early morning and late afternoon. Between exposures the mirrors were shielded from sunlight, and electric fans kept a continuous blast of air directed upon them. Even with these precautions there would frequently be a marked change of focal length during an exposure lasting four minutes. The distortion of the mirrors increased during the observations and strong evidences of astigmatism often appeared before they were completed. Except for occasional eruptions, the calcium, iron, and $H\delta$ flocculi change rather slowly in form, and one or two photographs taken daily with each line sufficed for the investigations in progress. In the case of $H\alpha$ it seemed probable that many photographs, separated by short time-intervals, would be needed to register the phases of rapidly changing phenomena. This would mean almost uninterrupted exposure of the mirrors to sunlight, and such serious distortion that the astigmatism would ruin the photographs.

At this point experience with the tower telescope came in to good advantage. The very thick mirrors used with this instrument are not appreciably distorted in sunlight.[2] Hence it seemed probable that by reducing the aperture of the Snow telescope mirrors the increase in their relative thickness would relieve the difficulty. I

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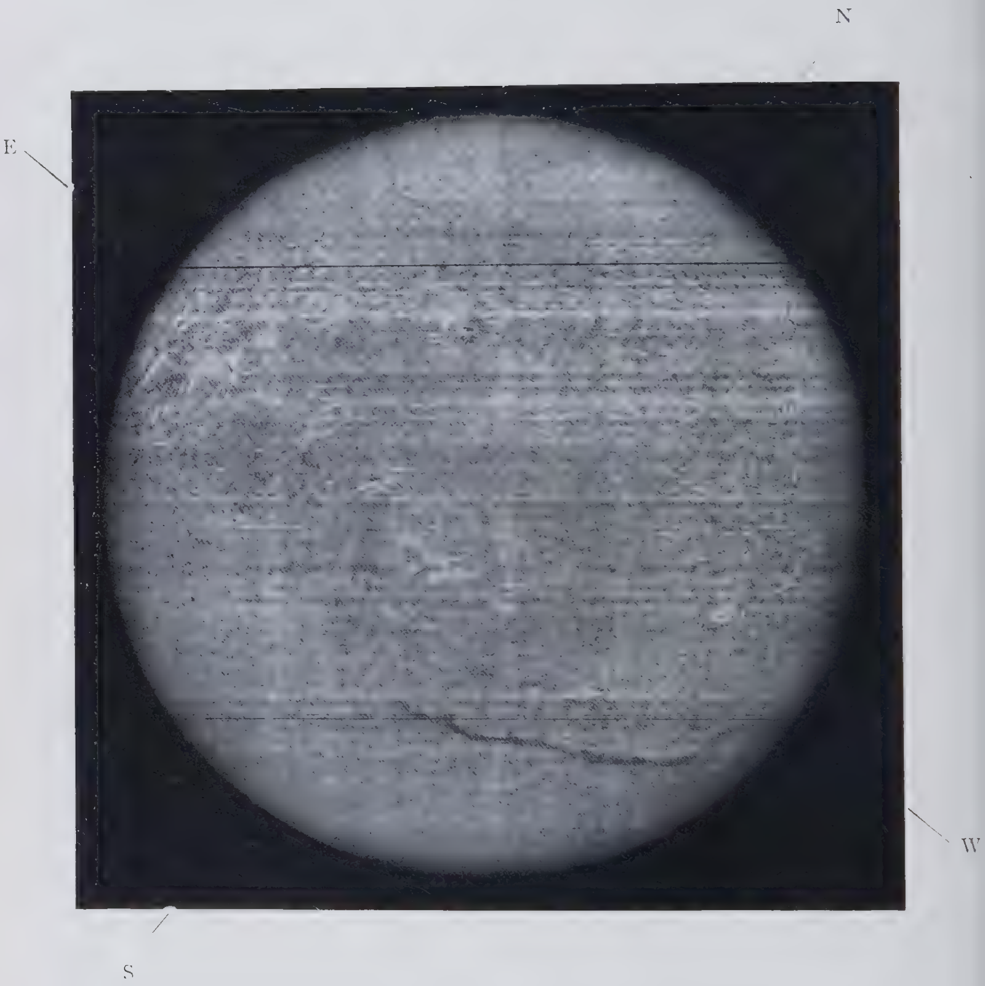
[1] Except the short interval required to obtain a direct photograph.

[2] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

PLATE XXXII



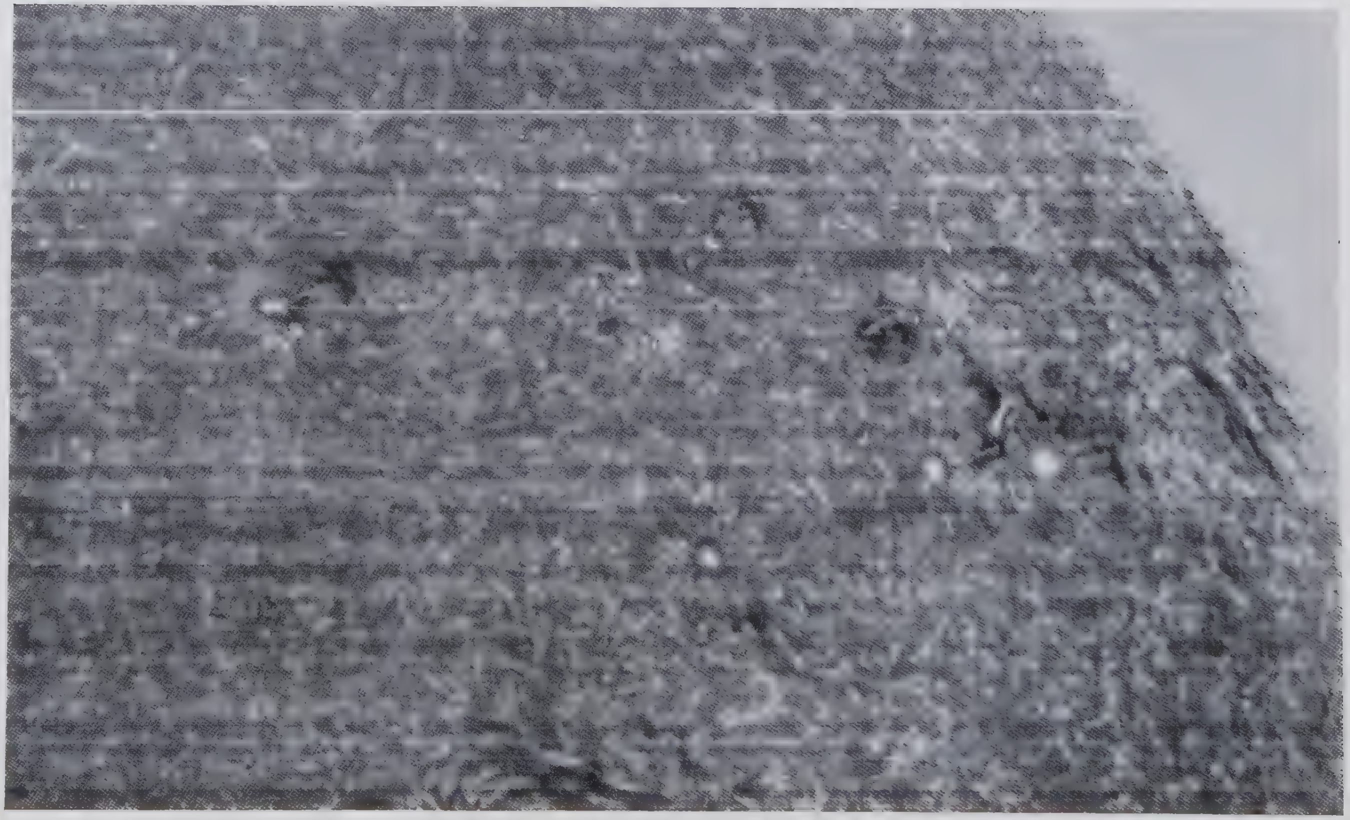
The Sun, Showing the Hydrogen ($H\alpha$) Flocculi
1908, April 30, $5^{h}\ 06^{m}$ P. M.

PLATE XXXIII

HYDROGEN ($H\alpha$) FLOCCULI

1908, April 30, $5^h\ 06^m$ P. M. Large scale *negative* print showing portion of Plate XXXII, reversed east and west. Scale: Sun's Diameter = 0.3 Meter

PLATE XXXIV



HYDROGEN ($H\alpha$) FLOCCULI SURROUNDING SUN-SPOTS

1908, April 30, 5^{h} 06^{m} P. M. Large scale *negative* print showing portion of Plate XXXII, reversed east and west

Scale: Sun's Diameter = 0.3 Meter

therefore commenced a series of experiments with different apertures, and finally adopted a 15-inch (38 cm) diaphragm for the coelostat in place of the full aperture of 30 inches (76 cm). With this the focal length does not ordinarily change perceptibly during a single exposure. When the mirrors are in sunlight, with very brief interruptions, during a period of an hour, the focal length gradually increases, but the effect of astigmatism is hardly appreciable.

In the work with $H\delta$, the hydrogen flocculi could not be photographed with sufficient contrast unless the very slow "Process" plates (also used for H_1 and H_2) were employed. These plates gave excellent results with $H\alpha$, but could not be used after the aperture had been reduced to 15 inches without undue increase of exposure time. Hence it was necessary to substitute for them Seed's "Gilt Edge" plates, which fortunately serve very well with this line. The first experiments with $H\alpha$ were made about the middle of March. On March 28 the new slits were in place, and the first photographs of the entire disk were obtained. During April the weather was not very favorable, but on April 29 and 30 Mr. Ellerman, then in charge of the routine work with the five-foot spectroheliograph, secured some remarkably fine negatives. The one taken on April 30 is reproduced in Plate XXXII. Apart from the whirls, which may be seen to better advantage in Plates XXXIII and XXXIV, this photograph shows in projection an enormous prominence in the southern hemisphere. This also appears, though much less satisfactorily, on the $H\alpha$ photograph of May 1, and may be traced on the $H\delta$ photograph of the same date (Plate XXX).

But in spite of its great intensity and length, this prominence is of minor interest in comparison with the structure shown in Plates XXXIII and XXXIV. This is so definite in form and so unmistakable in character as to satisfy the hopes aroused by the earlier photographs. It seems evident, on mere inspection of these photographs, that sun-spots are centers of attraction, drawing toward them the hydrogen of the solar atmosphere. Moreover, the clearly defined whirls point to the existence of cyclonic storms or vortices.

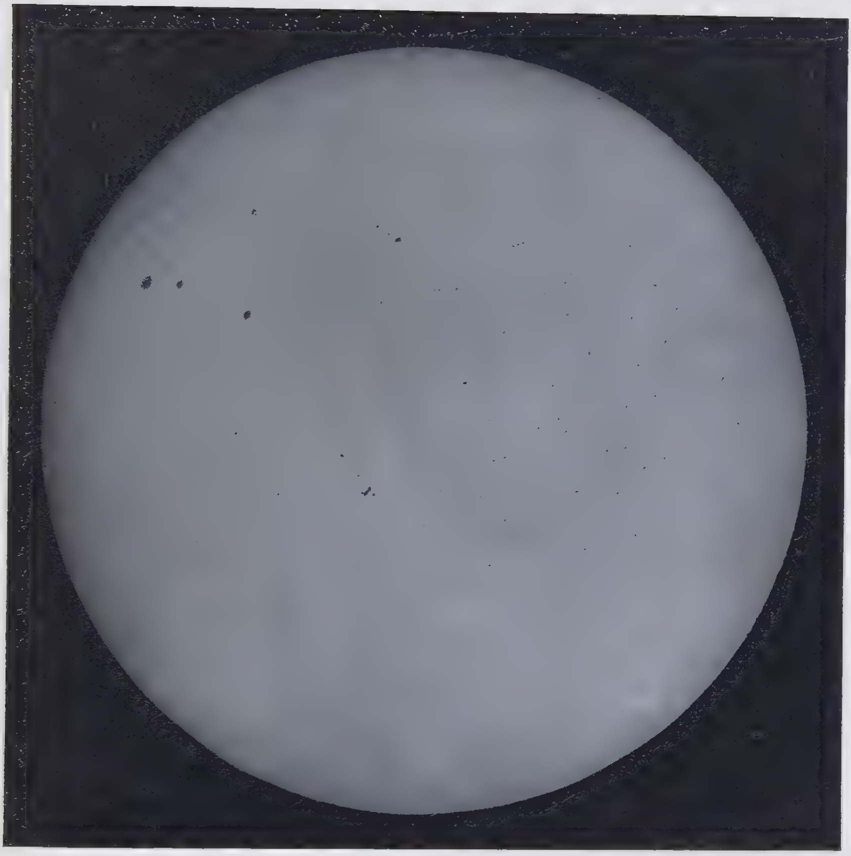
The most striking of these storms occupies an enormous area in the southern hemisphere, extending from the equator to about 35°

south latitude and about 50° in length. Near the center of this region, partly covered by clouds of bright hydrogen, lies the small spot-group shown (from a direct photograph) in Plate XXXV. The corresponding H_2 photograph reveals a large calcium flocculus over the spot-group (Plate XXXVI), but this, though of great size, appears to differ in no essential particular from ordinary calcium flocculi, and gives no evidence of gyratory motion.

A good $H\alpha$ photograph was obtained on April 29, but it was badly stained in the sensitizing process, and many of the flocculi are hidden by streaks on the negative. Fortunately, the greater part of the large storm area is fairly well shown, so that comparisons with the afternoon photograph of April 30 may be made in the stereo-comparator (using the monocular attachment). On account of the changes in form of the flocculi during this interval, the identification of objects suitable for measurement is very difficult and uncertain. Three independent determinations of the positions of certain flocculi on the two plates have been made by Miss Ware. The objects identified on both dates were marked by small dots of ink on the glass side of the negative, and their latitude and longitude measured with the heliomicrometer. When reduced to the same epoch (using for the value of the daily angular motion $\xi = 14\overset{\circ}{.}5$, derived from the measurement of 828 points on 35 $H\delta$ plates), the plotted results seem to show the existence of a gyratory motion, in a direction opposite to that of the hands of a watch (north, east, south, west). Although most of the points in a given region appear to move together, there are a sufficient number of apparently opposed motions to weaken seriously the value of the evidence. Unfortunately, an $H\delta$ plate taken on the morning of April 30 is not sharp enough to assist in the identifications. Further discussion of these plates is therefore postponed until additional data become available. On account of the complex character of such storms, a large number of photographs, taken at sufficiently short intervals to permit the flocculi to be identified with certainty, will be required to give satisfactory results. As our recent plates show that these storms are of common occurrence, and probably accompany every group containing several spots, there should be no difficulty in obtaining suitable photographs.

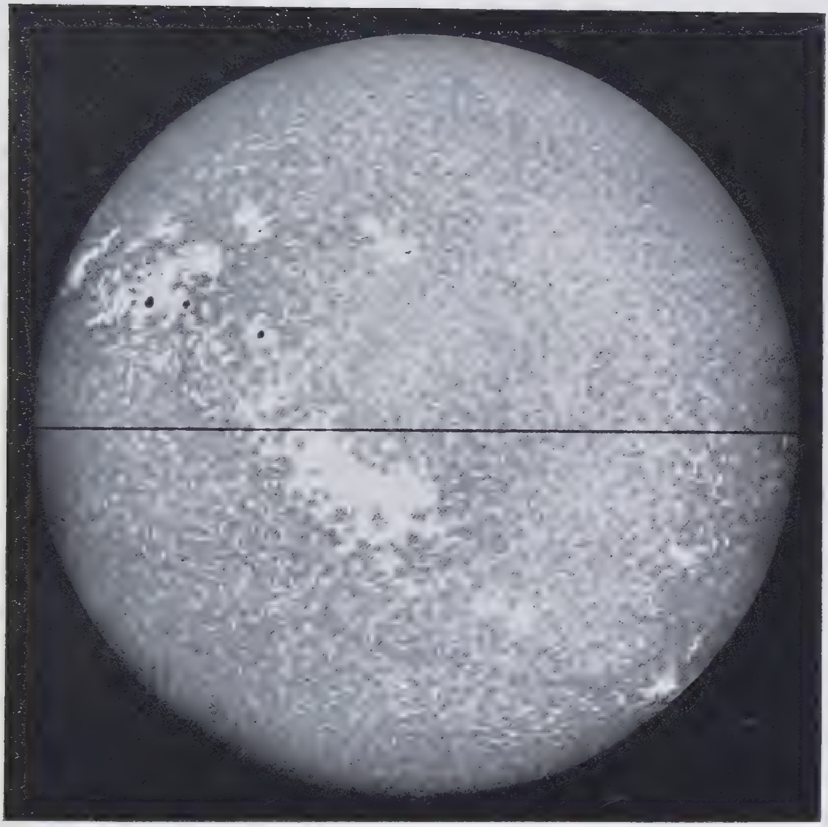
In the present paper I wish to illustrate the phenomena photo-

PLATE XXXV



Direct Photograph of the Sun
1908, April 30, $6^h\ 25^m$ a. m.

PLATE XXXVI



THE SUN, SHOWING THE CALCIUM (H_2) FLOCCULI
1908, April 30, 4^h 43^m P. M.

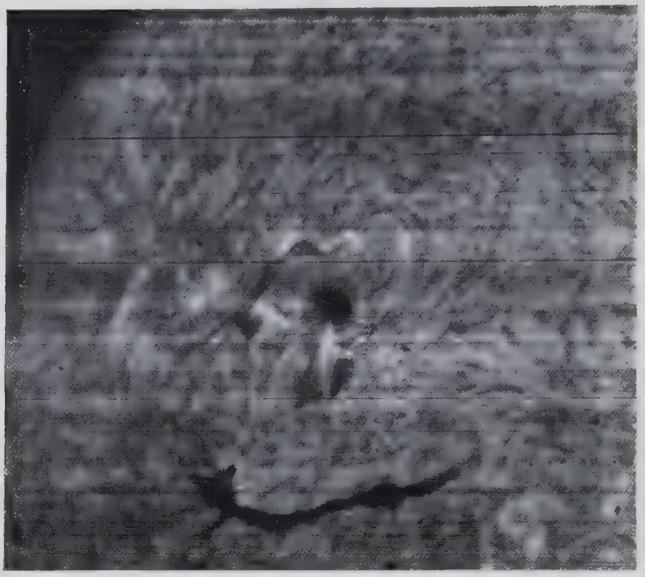


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^{h} 26^{m} P. M. Scale: Sun's Diameter = 0.3 Meter

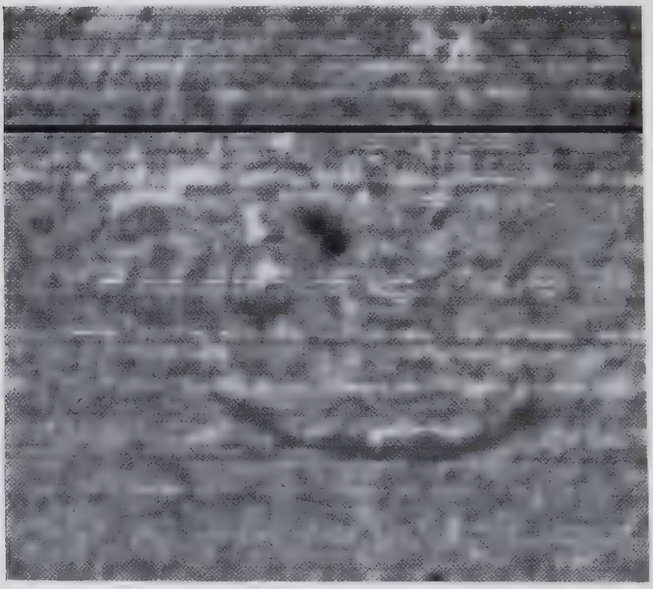


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 2, 6^{h} 10^{m} A. M. Scale: Sun's Diameter = 0.3 Meter

graphed with the aid of $H\alpha$ in the neighborhood of a spot which reached the east limb of the sun at $8^h\ 16^m$ A. M. on May 26, 1908. A photograph of this spot, made by myself with $H\alpha$ on May 29, at $4^h\ 26^m$ P. M. Pacific Standard Time, is reproduced in Fig. 1, Plate XXXVII. The whirl structure, which is clearly shown by this photograph, is also very distinct, though of somewhat different form, on the photograph of May 28. It is interesting to inquire as to the probable level of the region in which this whirl occurred, and the height of the long dark flocculus south of the spot. For this purpose we may examine photographs of the chromosphere and prominences at the limb, taken on May 25, 26, and 27. In the first of these, made on May 25 at $9^h\ 18^m$ A. M. (No. 4142), a long narrow prominence, extending toward the north, rises from the limb at position angle 92°, a point about one degree north of the spot. It makes an angle of about 12° with the limb, and fades out at the upper end, its length being approximately 90″ (geocentric). There are other small filamentary prominences in the region extending about 7° north of the spot, and smaller elevations in the chromosphere to the south. At P. A. 98° a bright prominence rises to a height of about 20″ and then slopes to the chromospheric level at P. A. 107°. Near its southern end is an independent filamentary prominence about 55″ high. On May 26, at $6^h\ 38^m$ A. M. (No. 4144), the prominences shown in Fig. 1, Plate XXXI, were photographed at the east limb. The lowest point in the chromosphere on this photograph corresponds to the position (P. A. 93°) where the spot crossed the limb about two hours later. It will be seen that these prominences, which extend from P. A. 82° to 106°, cover much of the region in which the whirl structure of Plate XXXVII appears. The prominence south of the spot is very bright and its highest point reaches an elevation of about 35″. On May 27, at $5^h\ 22^m$ P. M. (No. 4152), a prominence about 25″ high extends from position angle 105° to 109°. This is doubtless the eastern extremity of the strong flocculus in Plate XXXVII, which may be there seen curving toward the spot.

We may now pass in rapid survey the more important photographs of the disk. On May 28, at $6^h\ 58^m$ A. M. (No. 4157), the spot is near the east limb and the whirls are well shown. To the east of the spot is a long narrow line of bright hydrogen. On May 29, at

6^h 24^m A. M. (No. 4171), the whirls are very distinct and differ in many respects from those shown on May 28. Eruptive regions of bright hydrogen are seen southeast and west of the spot. The eastern end of the long dark flocculus is changing in form, and bridges are appearing over the spot. Negative No. 4175, taken 1^h 19^m later, seems to show distinct changes in the whirls, though they are not measurable. On May 29, at 4^h 26^m P. M. (No. 4176), the whirls resemble those shown in negative No. 4175, but exhibit some marked changes. An eruption which appears on the former plate southeast of the spot continues, but is changed in form and less brilliant than before. A strong eruption, of peculiar form, appears southwest of the spot, and bright hydrogen to the northeast. Strong dark flocculi have also developed at many points around the spot. The eastern end of the long dark flocculus is still changing, and a projection appears west of its center (see Plate XXXVII). A negative taken on the same day at 5^h 13^m P. M. (No. 4178) shows further changes in both bright and dark structure, especially in the region southwest of the spot. A fork has developed in the western end of the long dark flocculus, and a small but very dark flocculus appears just west of the spot. Another photograph (No. 4179), the first exposure of which was made at 5^h 26^m P. M., shows a bright eruption west of the spot, where the small dark flocculus appears on No. 4178. The eruption underwent considerable change of form while the five exposures on this plate, separated by intervals of a few minutes, were being made. At 6^h 04^m P. M. negative No. 4181 shows that the eruption had subsided and brings out other definite changes in structure near the spot. The small dark flocculus has disappeared. On May 31, at 8^h 09^m A. M. (No. 4188), the fork at the western extremity of the long dark flocculus has partially closed. No eruptions appear west of the spot, but there are bright ones to the southeast. Other important changes are evident, and the two bridges across the spot are conspicuous. On June 1, at 6^h 30^m A. M. (No. 4189), the fork at the western end of the long dark flocculus appears more nearly as it did in negative No. 4181, and the two bridges over the spot are very marked. A negative taken 15 minutes later (No. 4190) shows distinct changes, especially in the region south and southeast of the spot. At 5^h 08^m P. M. of the same day negative No. 4193 shows a

PLATE XXXVIII

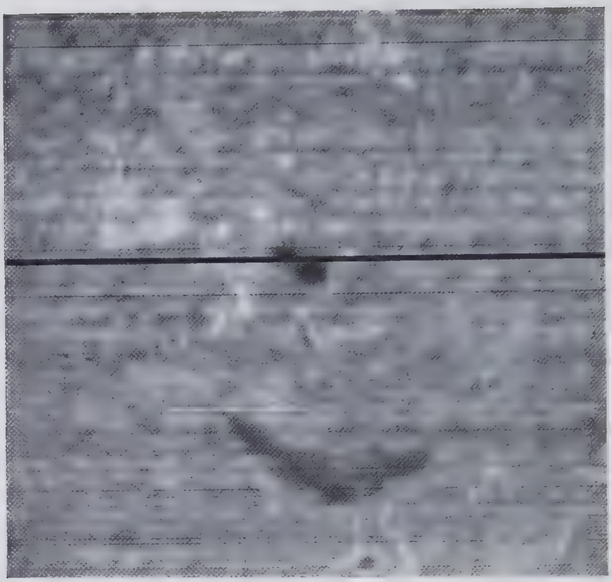


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 4^h 58^m 16^s P. M. Scale: Sun's Diameter = 0.3 Meter

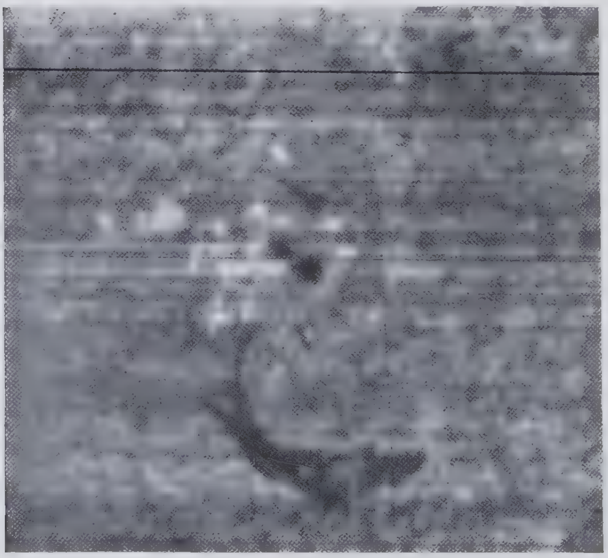


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 13^m 54^s P. M. Scale: Sun's Diameter = 0.3 Meter

PLATE XXXIX

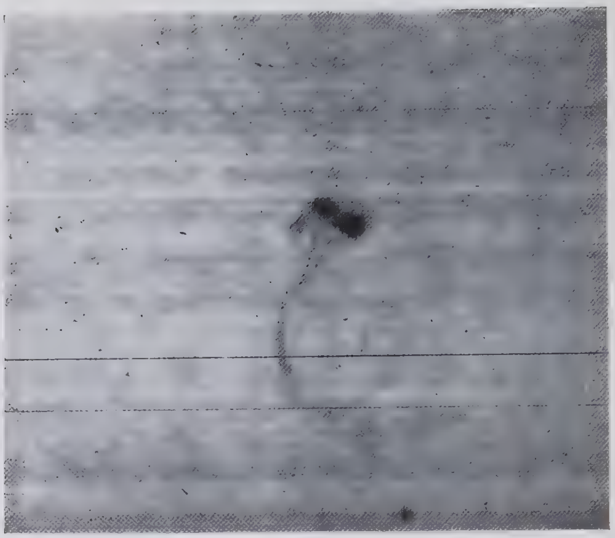


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 22^m P. M. Scale: Sun's Diameter = 0.3 Meter

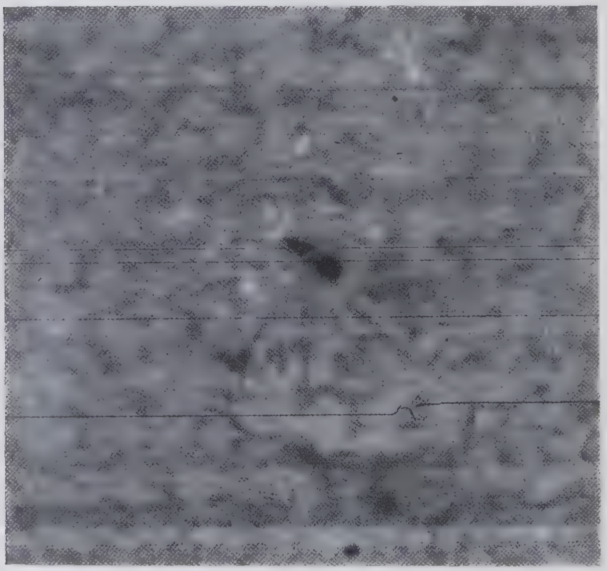


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 4, 6^h 12^m A. M. Scale: Sun's Diameter = 0.3 Meter

more distinct whirl near the spot, and the long dark flocculus appears to be growing shorter at its eastern end. On June 2, at 6^h 10^m A. M. (No. 4196), the whirling structure is very marked and more nearly symmetrical about the spot, which is divided into two parts (Fig. 2, Plate XXXVII). At 7^h 27^m A. M. (No. 4198) the whirl is also very marked and somewhat changed in form.

Up to this time the changes, while in many cases rapid, were not especially violent. On June 3, in an interval of about ten minutes, a remarkable transformation occurred. The long dark flocculus, which had been gradually changing in form and position, was suddenly drawn into the spot. As Fig. 2, Plate XXXVII, illustrates, the whirls were very conspicuous on the preceding day. A series of photographs, nine of which were made on negative No. 4201, between 4^h 48^m 09^s P. M. and 5^h 13^m 54^s P. M., and one, showing the entire disk, on negative No. 4202, at 5^h 22^m P. M., records the changes which took place during this time. These photographs were taken by Dr. C. E. St. John, who joined the Observatory staff in May, and is sharing with me the observational work with the five-foot spectroheliograph during Mr. Ellerman's absence on vacation. Three of these have been selected for reproduction. Fig. 1, Plate XXXVIII, is enlarged from a photograph made at 4^h 58^m 16^s P. M. (time of transit of spot across collimator slit of spectroheliograph). At 5^h 01^m 21^s the large dark flocculus is apparently unchanged in form. At 5^h 04^m 21^s an exposure, which is not quite so well defined, gives no certain evidence of change. The next exposure, made at 5^h 07^m 06^s, clearly shows the development of a fork at the eastern end of the flocculus, with traces of a very faint curved extension toward the larger spot. The position of the end of the fork (*C*), as measured on this photograph, is given below, but the extension is too faint to be measured with certainty. The next exposure, made at 5^h 10^m 52^s, shows the fork and part of the extension, but the definition is poor and the position of the end of the extension uncertain. The last exposure on this plate, made at 5^h 13^m 54^s, is reproduced in Fig. 2, Plate XXXVIII. This admits of fairly satisfactory measurement, the results of which are given below. The spot region on negative No. 4202, made at 5^h 22^m P. M. (time of transit of spot), is reproduced in Fig. 1, Plate XXXIX. Here the definition and contrast are also poor, but the extension, reaching nearly to the spots, is sufficiently well shown, as well as a dark flocculus which developed southeast of the smaller spot.

With the aid of the monocular attachment of the stereocomparator I have made a careful examination of all the photographs, and Miss Ware has measured the positions of the long dark flocculus with the heliomicrometer. If we call A the western extremity of this flocculus, B its eastern extremity, and C its point of nearest approach to the spot, we have the results of the measurements in Table I, which also include the positions of the two spots.

If we now take the measured differences in longitude and latitude of the large spot and the points A, B, and C respectively, and compute the corresponding distances, we have the results given in Table II.

These results show that the long dark flocculus gradually shortened, its eastern extremity apparently moving inward along the flocculus, while the distance of its western extremity from the spot did not change in a systematic manner. Accuracy of measurement is out of the question, as the flocculus varied so much in form from day to day that there can be no certainty in the identification of points that appear to correspond. A comparison of the series of photographs taken during the period of rapid development shows that the form and position of the main body of the flocculus did not greatly alter in this short interval, though the maximum of intensity moved rapidly toward the spots, leaving the body of the flocculus very faint. Even on these photographs, however, the velocity of the motion toward the spot cannot be precisely measured, partly because of the difficulty of determining where the extension ends and also because the time of the beginning of the phenomenon doubtless did not exactly coincide with the moment of exposure 6. Between exposures 6 and 7 we find for the point C a change of 1°9 in latitude and 1°5 in longitude. This corresponds to a motion of 2°4 in 195 seconds, or 177 km per second. Between exposures 7 and 9, in an interval of 408 seconds, there was a change of 3°0 in latitude and 0°4 in longitude, giving a velocity of 89 km per second. Eight minutes later[1] the extension had divided and moved nearly to the spots, the resultant motion for each extremity being 2°8, giving a velocity of 71 km per second.

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[1] The time of negative No. 4202 is recorded only to the nearest minute.

TABLE I

Negative No.	Date	Point	Longitude	Latitude	Remarks
4176..........	May 29, 1908 4h 26m P. M.	A	32°0 E	5°8 S	B and B′ are the two extremities of eastern end of flocculus
		B	48.6	13.6	
		B′	46.7	12.8	
		Spot	45.8	3.0	
		Spot	44.4	3.1	
4189..........	June 1, 1908 6h 30m A. M.	A	3.9 W	5.5 S	
		B	13.0 E	13.1	
		Spot	10.2	2.3	
		Spot	8.6	2.6	
4193..........	June 1, 1908 5h 08m P. M.	A	9.7 W	4.0 S	
		B	6.4 E	12.9	
		Spot	3.5	3.0	
		Spot	not measurable		
4196..........	June 2, 1908 6h 10m A. M.	A	16.9 W	5.5 S	A and A′ are the two extremities of western end of flocculus
		A′	16.2	4.5	
		B	2.9	12.4	
		Spot	2.8	2.8	
		Spot	4.1	3.1	
4201, Exp. 5...	June 3, 1908 5h 01m 21s P. M.	A	38.3 W	5.8 S	
		B	23.9	11.1	
		Spot	22.5	2.6	
		Spot	24.2	2.7	
4201, Exp. 6...	5h 04m 21s P. M.	A	35.8 W	8.2 S	
		B	23.6	11.2	
		C	25.5	11.1	
		Spot	22.5	2.6	
		Spot	24.4	2.8	
4201, Exp. 7...	June 3, 1908 5h 07m 06s P. M.	A	35.9 W	8.1 S	
		B	23.5	11.0	
		C	24.0	9.2	
		Spot	22.5	2.5	
		Spot	24.4	2.7	
4201, Exp. 9...	5h 13m 54s P. M.	A	35.5 W	8.0 S	
		B	23.6	11.0	
		C	23.6	6.2	
		Spot	22.6	2.6	
		Spot	24.4	2.7	
4202..........	5h 22m P. M.	C	23.0 W	3.5 S	C approaches eastern spot
		C′	23.8	3.4	C′ approaches western spot
		Spot	24.5	2.6	
		Spot	22.7	2.5	

TABLE II

No. and Date	Longitude			Latitude			Distance		
	A-Spot	B-Spot	C-Spot	A-Spot	B-Spot	C-Spot	A-Spot	B-Spot	C-Spot
4176, May 29, $4^h 26^m$ P. M. . .	+12°.4	−4°.2		+2°.7	+10°.5		12°.7	11°.3	
4189, June 1, $6^h 30^m$ A. M. . . .	+12.5	−4.4		+2.9	+10.5		12.8	11.4	
4193, June 1, $5^h 08^m$ P. M. . . .	+13.2	−2.9		+1.0	+ 9.9		13.2	10.3	
4196, June 2, $6^h 10^m$ A. M. . . .	+12.8	−1.2		+2.4	+ 9.3		13.0	9.4	
	+12.1			+1.4			12.1		
4201, June 3									
Exp. 5, $5^h 01^m 21^s$ P. M. . . .	+14.1	−0.3		+3.1	+ 8.4		14.4	8.4	
Exp. 6, $5^h 04^m 21^s$ P. M. . . .	+11.4	−0.8	+1.1	+5.4	+ 8.4	+8.3	12.6	8.4	8.4
Exp. 7, $5^h 07^m 06^s$ P. M. . . .	+11.5	−0.9	−0.4	+5.4	+ 8.3	+6.5	12.7	8.3	6.5
Exp. 9, $5^h 13^m 54^s$ P. M. . . .	+11.1	−0.8	−0.8	+5.3	+ 8.3	+3.5	12.3	8.3	3.6
4202, June 3, $5^h 22^m$ P. M. . . .			C–E. Spot =0.3 C′–W. Spot =0.7			C–E. Spot =0.8 C′–W. Spot =1.0			C–E. Spot =1.0 C′–W. Spot =1.1

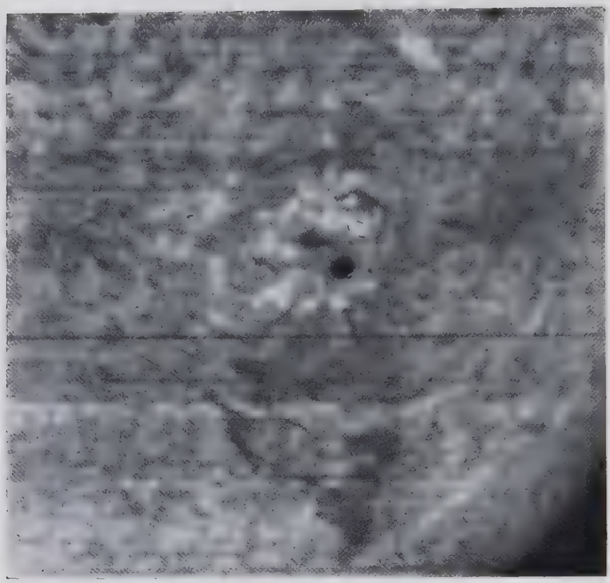

FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 5, $7^h\,05^m$ A. M. Scale: Sun's Diameter = 0.3 Meter

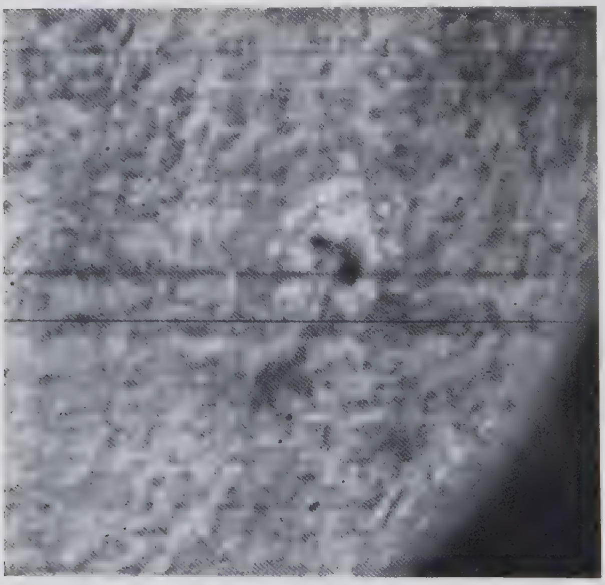

FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 5, $5^h\,19^m$ P. M. Scale: Sun's Diameter = 0.3 Meter

In order to check these measures, the stereocomparator was used to mark all of the points on a single plate, which was then measured differentially. The resulting velocities came out 140, 86, and 76 km per second respectively. Since the errors due to imperfect superposition in the stereocomparator should not differ markedly from those arising from a similar source in the heliomicrometer, the second set is given the same weight as the first. The differences among the three velocities cannot be trusted, though the evidence favors the view that the first velocity was actually higher than the others. The mean of the six measures (106 km) will at least serve to give the order of the maximum velocity in the vortex.

The appearance of the spot and surrounding region 13 hours after the rapid changes described above is shown in Fig. 2, Plate XXXIX. The straight radial lines in this photograph are in marked contrast to the curved structure previously shown. The eastern of the more plainly marked radial lines is found by measurement to be a short distance to the east of the extension from the large flocculus to the spots shown in Fig. 2, Plate XXXVIII. The forked connection to the two spots has disappeared and a strong dark flocculus has developed at the southern extremity of the radial line, mainly on its eastern side. With the stereocomparator the main body of the large flocculus is found to resemble its former appearance in some particulars, but the distribution of intensities is very different and many changes in outline have occurred. In the photograph of June 5, $7^h 05^m$ A. M. (No. 4220), the radial structure surrounding the spots is greatly altered and the flocculus, no longer recognizable, has developed a large extension toward the west (Fig. 1, Plate XL[1]). A notable feature of this photograph is the amount of bright eruptive hydrogen in the region surrounding the two spots. Some eruptive matter also appears in the photographs of the preceding day, but here it is greatly augmented. A photograph taken on the same day, at $5^h 19^m$ P. M. (No. 4227), is reproduced in Fig. 2, Plate XL. It will be seen that the eruptions continue, and that the dark flocculi have undergone further important changes. The most notable of these is the connection which appears to be re-established between the two spots and the dark flocculus south of them. Apparently the dark hydrogen is again being drawn into the spots. On June 7, at 7^h 56^m A. M. (No. 4244), a faint prominence appears on the limb south of the position of the spot. On June 8, at 7^h 42^m A. M., negative No. 4252 shows a group of prominences closely resembling in form those reproduced in Fig. 1, Plate XXXI, but very much less brilliant. On June 9 no prominence was photographed in this region.

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[1] There is a defect in this plate near the spots.

As already remarked, the distance from the spot of the western extremity of the large flocculus did not vary systematically. The eastern extremity, on the contrary, commenced on June 1 to approach the spot, and continued to do so until the sudden change occurred on June 3. Up to this time the velocity, instead of showing signs of acceleration, was apparently retarded, but the changing form of the flocculus leaves this point uncertain. On the photograph of May 29 (No. 4176) the whirl is most conspicuous north of the spot, where its extreme distance is about equal to that of the western end of the large flocculus. Apparently, however, the flocculus did not fall completely under the influence of the vortex until June 1, when its eastern extremity was $11^\circ.4 = 140{,}000$ km from the spot. The fact that the minimum distance of the western end always exceeded this quantity may account for its escape.

In view of the nature of the phenomena described in this paper, and the fact that evidences of whirls or radial structure have been shown, in connection with several different spots, on a large number of $H\alpha$ photographs, one is greatly tempted to enter at once into a discussion of the sun-spot theories of Faye, Reye, Emden, Halm, Bigelow, and Eckholm, all of which assume the existence of cyclones or vortices within the photosphere or the solar atmosphere. It is the part of prudence, however, to defer such discussion until our daily increasing supply of photographs is considerably enlarged. Moreover, I have devised improved methods for comparing photographs, which should facilitate the identification of objects for measurement, and experiments are also in progress with the purpose of bringing more clearly before the eye the nature of the changes which take place within the vortices. A simple kinetoscope has been advantageously used to observe the rapidly changing phenomena of June 3, and more elaborate apparatus of this kind will soon be available.

It may be well to direct attention, however, to certain points which have been noted:

1. In the series of photographs (on negatives Nos. 4201 and 4202) which show the large flocculus in the act of being drawn into the spots, the small flocculi near the spots remain almost unchanged in position, perhaps because of difference of level.

2. Except in the case of the large flocculus, attempts to detect evidences of motion toward the spots have not yet proved successful, even along apparent lines of flow.

3. Negative No. 4196, taken on June 2, shows a dark comet-like object (apparently defining a line of flow) intersecting a bright eruptive flocculus. The appearance suggests that the eruption does not rise to the level of the vortex.

4. Photographs of the $H\alpha$ line across bright flocculi, made in the second- and third-order spectra of the 30-foot tower spectrograph, indicate that this line has a complex structure which will require careful investigation.

5. Since the velocity of the hydrogen drawn into the vortex is of the same order as that of eruptive prominences, distortions of the hydrogen lines at the limb may be due to the motion of this gas in vortices. If the line of sight were to pass through a vortex, distortions toward violet and red observed at the same point might result from motions of approach and recession on opposite sides of the vortex.

6. The appearance of numerous hydrogen eruptions after the event of June 3 suggests that the hydrogen drawn down by the vortex subsequently rose to the surface in the neighborhood of the spots.

7. In view of the fact that the distribution of the hydrogen flocculi frequently resembles that of iron filings in a magnetic field, it is interesting to recall the exact correspondence between the analytical relations developed in the theory of vortices and in the theory of electro-magnetism.[1]

8. The gradual separation of the spots should not be overlooked.

Without entering at present into further details, a single suggestion relating to the possible existence of magnetic fields on the sun may perhaps be offered. We know from the investigations of

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[1] See Lamb, *Hydrodynamics*, third edition, p. 201.

Rowland that the rapid revolution of electrically charged bodies will produce a magnetic field, in which the lines of force are at right angles to the plane of revolution. Corpuscles emitted by the photosphere may perhaps be drawn into the vortices,[1] or a preponderance of positive or negative ions may result from some other cause. When observed along the lines of force, many of the lines in the spot spectrum should be double, if they are produced in a strong magnetic field. Double lines, which look like reversals, have recently been photographed in spot spectra with the 30-foot spectrograph of the tower telescope,[2] confirming the visual observations of Young and Mitchell. It should be determined whether the components of these double lines are circularly polarized in opposite directions, or, if not, whether other less obvious indications of a magnetic field are present. I shall attempt the necessary observations as soon as a suitable spot appears on the sun.

Mount Wilson Solar Observatory
June 20, 1908

REMARKS ON THE PLATES

As it seems to be impossible to obtain illustrations which accurately represent the original negatives, certain remarks regarding the plates are required.

Plate XXX.—Both figures are fairly satisfactory except that the limb of the sun, in the lower right-hand corner, is not properly shown.

Plate XXXI, Fig. 1.—The position angles of various points in the prominences are given in the text of the article. The faint parallel lines, which make an acute angle with the sun's limb, are due to a slight irregularity in the motion of the spectroheliograph.

Plate XXXI, Fig. 2.—The black dots are defects produced in the sensitizing process.

Plate XXXI, Fig. 3.—The parallel lines are due to the cause mentioned above.

Plate XXXII.—This plate will serve to give a general idea of the appearance of the $H\alpha$ photograph of April 30, but fails to show the flocculi in their proper intensity. Although many bright flocculi appear to be present, especially in the upper part of the image, the original negative actually shows very few of these objects, the most conspicuous ones being in the midst of the great storm area in the southern hemisphere. For details see Plates XXXIII and XXXIV. The parallel vertical bands are due to a periodic motion of the spectroheliograph.

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[1] J. J. Thomson, *Conduction of Electricity through Gases*, p. 164.

[2] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Plate XXXIII.—As it was found by experiment that the flocculi on the photograph of April 30 are most accurately represented on a negative print, Plates XXXIII and XXXIV are reproduced in this way. Thus the light objects on both of these plates represent the dark $H\alpha$ flocculi. The dark structure in the midst of the storm area in Plate XXXIII is luminous hydrogen. The quality of this plate is more satisfactory than that of any other in the present collection.

Plate XXXIV.—This gives a fair idea of the flocculi in this region, though the limb is not well reproduced and certain regions near the spots and in the lower part of the plate are too black.

Plate XXXV.—The scale is so small that this illustration serves merely to indicate the distribution of the sun-spots on April 30, and the apparently insignificant nature of the group lying within the great storm area (near the center). The orientation is the same as for Plate XXXII.

Plate XXXVI.—This gives a fair idea of the appearance of the calcium (H_2) flocculi, though the limb is not well reproduced. The orientation is the same as for Plate XXXII.

Plate XXXVII, Fig. 1.—The only bright flocculi that should appear in this figure are those in the neighborhood of the spot.

Plate XXXVII, Fig. 2.—The background comes out too bright, giving the appearance of bright flocculi in regions where they are not present. The only objects of this class shown by the original negative are very conspicuous in the figure.

Plate XXXVIII, Fig. 1.—This gives a fair idea of the original negative, the contrast of which is not very strong.

Plate XXXVIII, Fig. 2.—The contrast of the original is much stronger than in the case of Fig. 1, hence the bright flocculi near the spot are relatively too conspicuous. The background in the upper part of the figure is also too bright.

Plate XXXIX, Fig. 1.—The original is lacking in contrast. The region to the left of the spot should be much darker than it appears in the cut.

Plate XXXIX, Fig. 2.—This is a fairly satisfactory reproduction, though the bright flocculi should be somewhat stronger.

Plate XL, Fig. 1.—Except for a defect in the photograph, the bright flocculi surrounding the spot are fairly well shown. In other parts of the figure, however, the background comes out too bright.

Plate XL, Fig. 2.—This is a fairly satisfactory reproduction, though the background is too bright in various places.

PLATE XLI

THE PASADENA LABORATORY

Contributions from the Mount Wilson Observatory, No. 27
Reprinted from the *Astrophysical Journal*, Vol. XXVIII, pp. 244–249, 1908

THE PASADENA LABORATORY OF THE MOUNT WILSON SOLAR OBSERVATORY

By GEORGE E. HALE

The spectroscopic laboratory erected in 1905 on Mount Wilson was described in *Contributions from the Observatory*, No. 10.[1] As stated in that paper, our investigations of sun-spot spectra made it necessary to supplement the equipment provided on Mount Wilson with a large electric furnace, which was installed in the Pasadena instrument shop. As the further development of our sun-spot work demanded the use of a more perfect electric furnace and as our apparatus required more current than could be economically generated on Mount Wilson, it seemed advisable to take advantage of the opportunity afforded in Pasadena to obtain electrical energy, at moderate cost, from the Edison Company. Accordingly a small laboratory, adjoining our instrument shop and standing immediately in front of the Hooker Building, was erected during the winter of 1908 (Plate XLI).

In the Mount Wilson laboratory the various light-sources are arranged on the circumference of an annular pier. A plane mirror at the center, which can be rotated about a vertical axis, reflects the rays from the light-source under examination to a concave mirror, which forms an image on the slit of a horizontal Littrow spectrograph of 18 feet (5.5 m) focal length. In the Pasadena laboratory, profiting by experience with the tower telescope,[2] a vertical Littrow spectrograph, of 30 feet (9.1 m) focal length, is mounted in a well, with waterproof brick walls, extending 30 feet below the surface of the ground. The electric furnace and other light-sources stand on separate piers, arranged in a circle about the center of the spectrograph slit. The spectrograph can be rotated about the axis of the collimator and light from any source is reflected into the slit by means of a plane mirror standing (at 45°) above it (Plate XLII).[1]

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[1] *Astrophysical Journal*, **24**, 61, 1906.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

This arrangement determines the general plan of the laboratory (Fig. 1). The outside dimensions of the building are 32×44 feet. The walls are of brick, the floor of cement, and the ceiling of corrugated iron. The well which contains the spectrograph, 8½ feet inside diameter, is near the middle of the principal room. As the spectrograph stands eccentrically, near one side of the well, considerable space is left in the well for other instruments requiring constant temperature conditions.

Except in one particular, the 30-foot spectrograph is precisely similar to the one used with the tower telescope.[2] In addition to an 8-inch (20.3 cm) objective of 30 feet focal length, it is supplied with a 5-inch (12.7 cm) objective of 13 feet (4 m) focal length.[3] This objective, together with an adjustable grating-holder mounted in conjunction with it, can be swung out of the axis of the spectrograph when the objective of 30 feet focal length is to be employed. Thus a considerable range of dispersion, from the first-order spectrum with the 13-foot objective to the fourth-order spectrum with the 30-foot objective, is available. Both objectives can be focused from the eye-end of the instrument and the grating can be rotated from the same point. The only gratings at present available are a 5-inch Rowland plane, having 14,438 lines to the inch, kindly loaned to us by the Johns Hopkins University, and a 4-inch Michelson plane, having 500 lines to the millimeter.

The concrete floor is continued over the well, the spectrograph ring being supported on a cylinder of concrete rising from it. The temperature at the bottom of the well is so constant that exposures of any desired length can be given, without fear of displacement of the lines arising from changes in the temperature of the grating.

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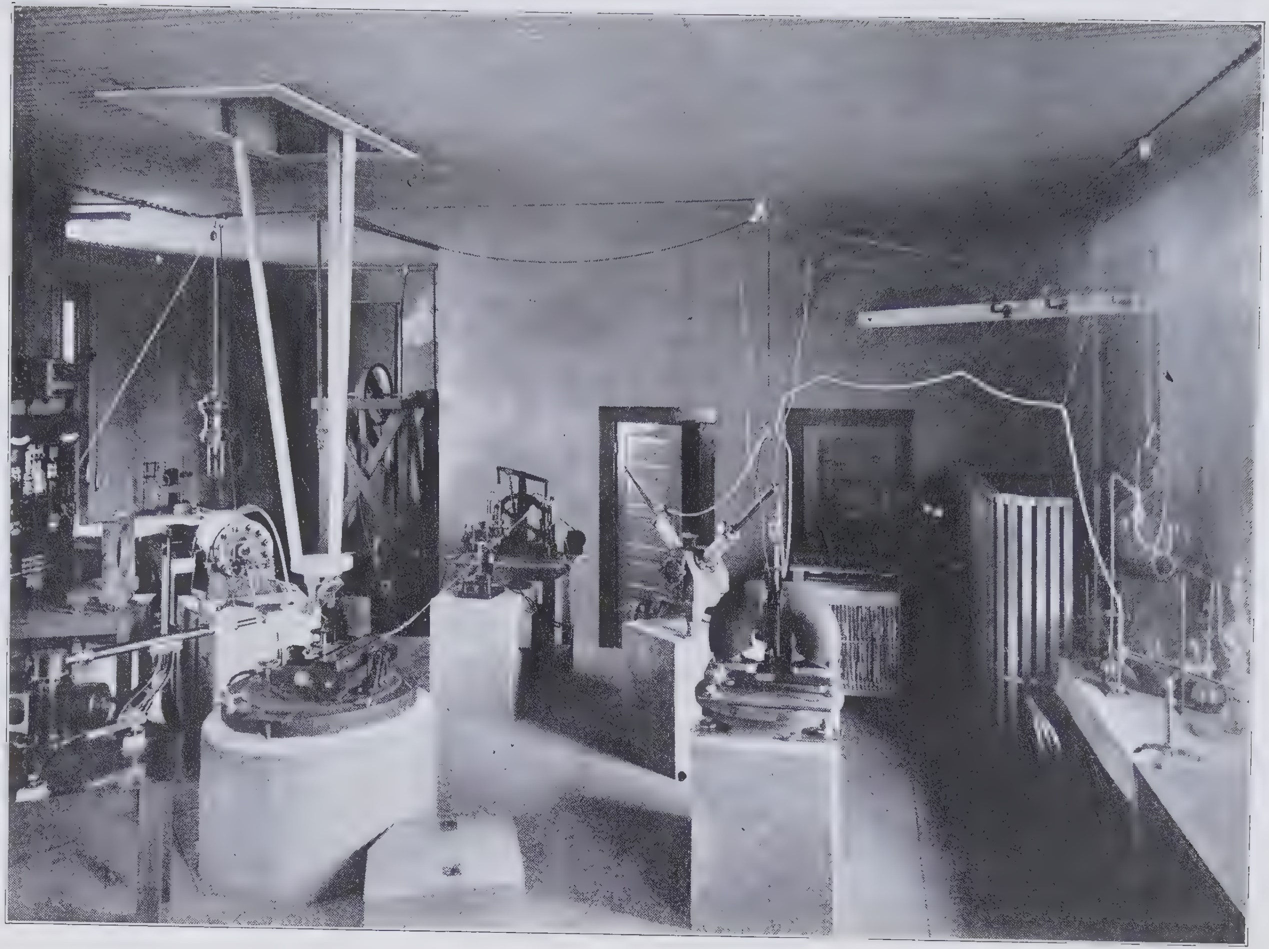
[1] The mirror support shown is a temporary one, and will be replaced later by a different apparatus, carrying also a lens, on a radial arm, to form an image of any source on the slit.

[2] *Loc. cit.*

[3] Both visual and photographic objectives of this size, formerly employed in photographing spectra with the Snow telescope, are available for use with this spectrograph.



Interior of the Pasadena Laboratory

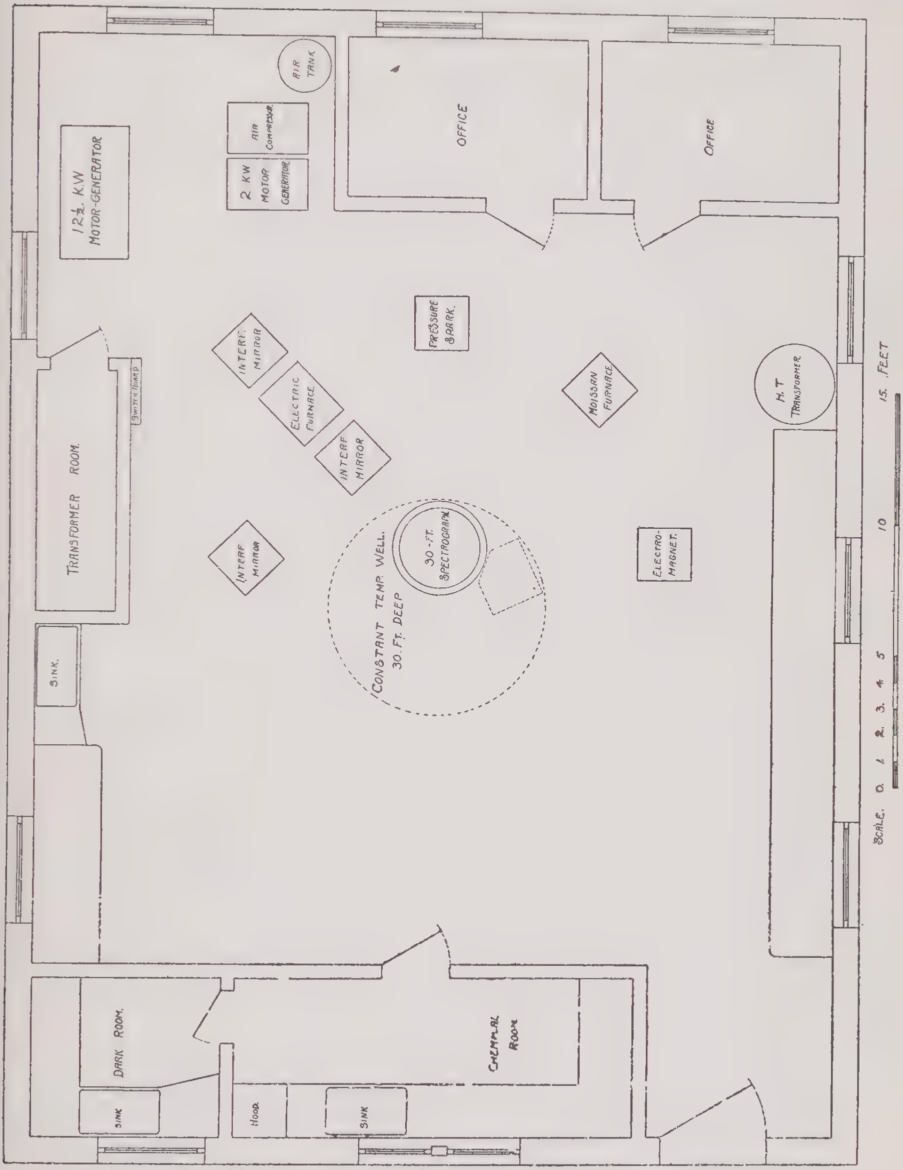


FIG. 1.—Plan of Laboratory

A small fireproof room in the laboratory contains five transformers, connected with the 2000-volt alternating current circuit of the Edison Electric Company, as follows:

a) One low-voltage transformer, formerly used for our experiments on fused quartz, having a capacity of 50 K.W., with connections for 5, 10, 20, or 30 volts. By means of very heavy copper cables, passing through a conduit beneath the floor, this transformer supplies the resistance-tube electric furnace with current.

b) Two 30 K.W. transformers, primarily for heavy-current arc work. These may be connected either in series or parallel, giving 52 or 104 volts, with a capacity of 60 K.W., or 208 volts, with a capacity of 30 K.W.

The secondary terminals of transformers *a*) and *b*) are mounted on a slate pier in the transformer room, where they may be joined by heavy copper lugs to cables passing through conduits to the three piers designed for furnace and arc work. Thus the voltages above mentioned, ranging from 5 to 208, are available as desired at any one of these piers. The three transformers are controlled by primary oil switches, operated by cords from without the transformer room.

c) Two 15 K.W. transformers, which supply power to the machinery of the instrument and optical shops, to the motors that drive the direct-current generators in the laboratory, to the high-voltage transformer, etc.

The 5 K.W. high-voltage transformer, which stands on the opposite side of the room, is connected with highly insulated overhead wires passing across the laboratory, from which leads may be dropped to any of the piers where a spark is to be used. This transformer contains a series of step-up connections, giving 1000, 2000, 4000, 8000, 16,000 32,000, or 64,000 volts at the secondary terminals. Within the inclosure which surrounds the transformer there are a series of self-induction coils and a large condenser, consisting of alternate plates of sheet metal and plate glass immersed in oil.

Direct current is supplied from two sources:

a) A 12½ K.W. dynamo, direct connected with a three-phase motor. Both of these machines stand on a heavy concrete pier, separated from the floor and resting on a bed of sawdust. In this way the vibration is so greatly reduced that it is not perceptible in the 30-foot spectrograph. By regulating the field of the motor the dynamo gives voltages varying from 30 to about 120. Thus the DuBois electro-magnet, which is intended for use at 64 volts, can be excited without a series rheostat. The high voltage is mainly employed for powerful electric current arcs and other similar purposes.

b) A 2 K.W. generator, direct connected with a three-phase motor, both standing on a pier separated from the floor. This gives direct-current voltages ranging from 90 to 120, and serves well for small arcs and other apparatus requiring moderate currents. The motor is also used to drive an air-compressor built by Cook of Manchester, after a design kindly prepared for us by Mr. Petavel.

Both dynamos are joined to the switchboard, where they may be connected to wires passing through conduits to two of the piers.

The principal light-sources and auxiliary instruments now employed in the laboratory are as follows:

a) A carbon or graphite tube resistance furnace (on the left of Plate XLII), inclosed in a steel cylinder capable of withstanding pressures up to 200 atmospheres. This furnace, which was designed by Dr. King, is described by him in another article.[1] The highest temperature hitherto attained in it, as measured with a Wanner pyrometer, is 3015°C. It has thus served admirably for the study of the spectra of such refractory metals as titanium and vanadium, permitting the relative intensities of their lines to be recorded at widely different temperatures. This furnace is also intended for investigations of anomalous dispersion, in conjunction with a Michelson interferometer and the 30-foot spectrograph.

b) A rotating arc in a pressure chamber, formerly used in the Mount Wilson laboratory.

c) An inclined arc electric furnace (near the middle of Plate XLII), similar in type to one used by Moissan, but modified according to designs by Dr. Olmsted so as to permit the arc to be observed in an atmosphere of hydrogen or other gas. For regulating the current a large rheostat is provided. This furnace is now used by Dr. Olmsted in his work on the fluted spectra of calcium hydride and other compounds found in the spectra of sun-spots and red stars. A Geryk duplex vacuum pump, driven by a small electric motor, is used with the two furnaces when low pressures are required.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28.

d) Spark terminals, mounted between the poles of a large DuBois electro-magnet formerly used in the Mount Wilson Laboratory. This apparatus, which is shown on the right of Plate XLII, is being used for the study of the Zeeman effect in the spectra of iron, titanium, and other elements that occur in the spectra of sun-spots.

e) An ordinary electric arc, used for comparison spectra, etc.

A one-prism quartz spectrograph and a direct vision spectroscope are employed for the preliminary examination of spectra. Other apparatus used in the Mount Wilson Laboratory and described in *Contribution* No. 10 is also available. A two-mirror heliostat, mounted on the roof immediately above the 30-foot spectrograph, supplies sunlight for comparison spectra. Piers for vacuum tube apparatus and other light-sources will be erected as occasion demands.

At the west end of the building there is a small chemical laboratory and a photographic dark-room. At the east end are the offices of Dr. King, superintendent of the Physical Laboratory, and Dr. Olmsted.

A more detailed account of the instruments used in the laboratory will appear in subsequent papers.

MOUNT WILSON SOLAR OBSERVATORY
August 1908

Contributions from the Mount Wilson Solar Observatory, No. 28
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AN ELECTRIC FURNACE FOR SPECTROSCOPIC INVESTIGATIONS, WITH RESULTS FOR THE SPECTRA OF TITANIUM AND VANADIUM

By ARTHUR S. KING

In designing an electric furnace for spectroscopic work in the laboratory of the Mount Wilson Solar Observatory, several requirements were kept in mind.

1. An apparatus which should give a long, uniformly heated column of vapor which might be brought to a temperature not very much below that of the electric arc. This need was shown by preliminary experiments which demonstrated the difficulty of producing by furnace methods the spectra of refractory substances such as titanium and vanadium, highly important in solar investigations.

2. Regulation of the furnace temperature, so that the direct effect of varying temperature might be observed, when other conditions remained unchanged.

3. The control of the conditions surrounding the luminous vapor, to observe the effect of changes in pressure and surrounding atmosphere. If spectra can be produced giving almost as many lines as the arc, the superiority of the furnace is manifest in that the effect of external influences such as pressure may be observed without an accompanying change in the action of the light-source itself, such as must take place in the arc or spark under pressure.

4. The possibility to observe absorption effects given when white light is passed through the highly heated vapor in the furnace.

The development of electric furnace work has shown that the type known as the "tube resistance furnace" is the one best adapted to all of these requirements. The temperature in such a furnace is regulated by the strength of the current passing through a tube, usually of carbon or graphite, supported horizontally and containing the substance to be vaporized. Such a tube must of course be protected from contact with the air, which would cause it to be quickly consumed. The best protection has been found to be a vacuum or a neutral gas around the tube. The inclosure in which the tube is placed for this purpose may be made strong enough to withstand any desired pressure. Such an apparatus, with a regulated current supply to the tube and windows in the walls of the chamber through which the interior of the tube could be observed, would fulfil the several purposes already outlined.

The furnace will be only briefly described in this paper, with a short account of its performance in the first investigation undertaken. The complete description, with detailed drawings, and the full discussion of the results with their bearing on astrophysical problems will be left for a later paper in the *Publications* of the Solar Observatory.

Plan of furnace.—The method adopted for the construction of the furnace was to arrange all of the essential parts in the form of a cartridge attached to one of the heads of a steel chamber, this chamber being built to stand high pressures. The arrangement is clearly shown in the photograph of the open furnace (Plate XLIII, Fig. 1). A half-cylinder of iron, screwed firmly to the head of the pressure chamber, contains two graphite blocks which serve to hold the ends of the horizontal resistance tube, and also establish contact between these ends and the copper pipe electrodes which pass through the steel head and carry the electric current. These graphite blocks are each 2 inches thick, about 6 inches wide at the middle, and in three sections. The block for the lower electrode has its top cut low enough to allow the passage of the upper electrode. The blocks are provided with vertical bolts $\frac{3}{8}$ inch in diameter, which hold the sections of the block together and when tightened make firm contact between the copper electrodes and the ends of the resistance tube. Sheets of asbestos or mica under the blocks secure insulation from the iron half-cylinder.

The length of the upper electrode at present employed permits the use of resistance tubes 16 inches long, with 9 inches to be heated between the blocks. Shorter tubes may of course be used by placing the blocks closer together, as contact can be made at any point along the upper electrode. With a longer pipe above, the size of the

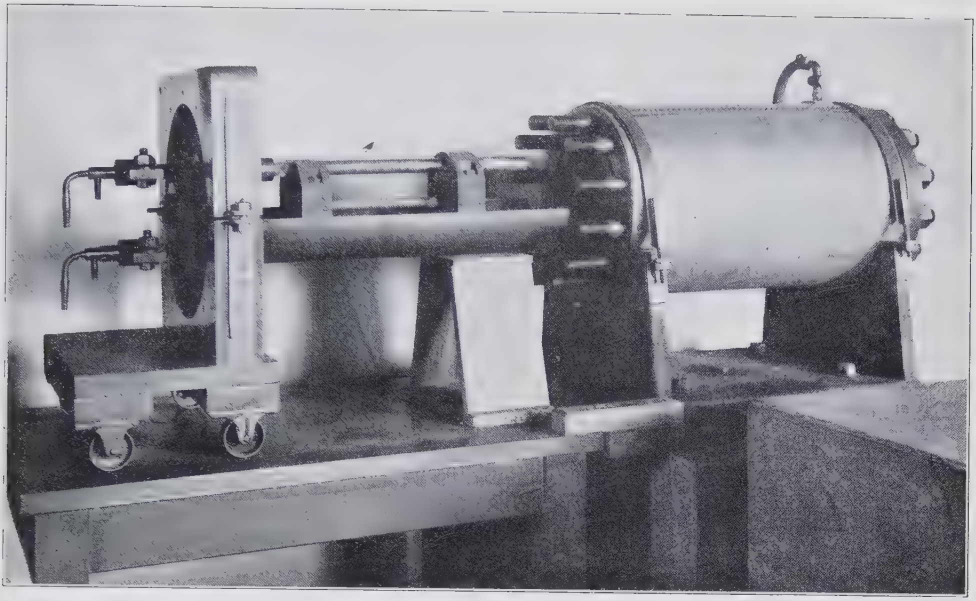

FIG. 1.—ELECTRIC FURNACE OPEN, WITH JACKETING MATERIAL REMOVED

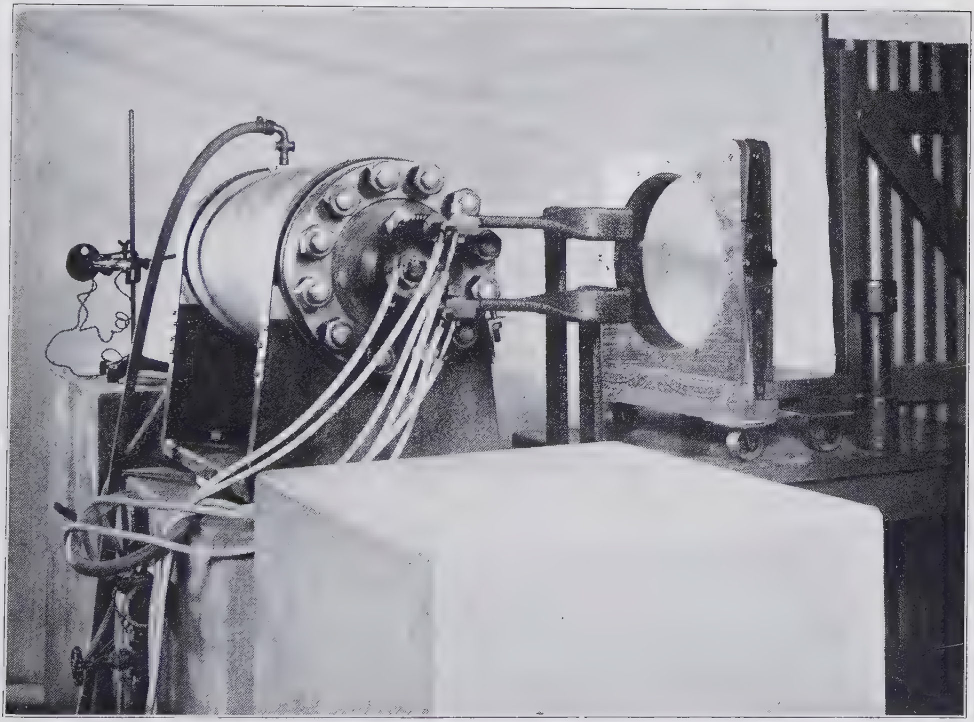

FIG. 2.—ELECTRIC FURNACE CLOSED, IN POSITION

inclosing chamber would permit the use of a resistance tube about 22 inches long, with 18 inches heated.

The jacketing about the resistance tube for heat insulation is not shown in the photograph. It was found, as has been noted by other workers in this field, that any jacketing material placed in contact with the resistance tube will fuse to some extent and conduct part of the current. The jacketing now in use works well. A carbon tube was made by boring out a rectangular block (round would serve as well) from end to end with a hole ¼ inch larger than the resistance tube to be used. The length was ½ inch less than that of the resistance tube between blocks, the walls no thicker than necessary to secure strength. This tube was split from end to end so that it could be placed around the resistance tube after the latter was in position, giving a free space of about ⅛ inch all around the resistance tube. The space between this carbon protector and the iron half-cylinder was then filled with carborundum powder, a complete jacketing being obtained by heaping the carborundum entirely over the carbon protector, stiff sheets of mica at the sides of the iron half-cylinder enabling this to be done.

Electrodes.—The current is carried to the ends of the resistance tube by two copper pipes passing through the cylinder head in insulated bushings. Each pipe is made of two tubes, one inside the other, of ½ inch and ¾ inch iron pipe size respectively, giving a tube of ⅝ inch I. D. and $1\frac{1}{16}$ inch O. D. This pipe is plugged at the inner end and the water cooling is given by a thin-walled copper tube, supported coaxial with the electrode pipe, carrying water to one inch from the end of the latter, the water then flowing back and bathing the inner wall of the electrode. A heavy copper lug connects the copper pipe outside the cylinder head to a copper bar ½×2½ inches which passes to the terminals of the cable from the transformer.

Resistance tubes.—The tubes thus far employed have been of either agglomerated carbon or Acheson graphite, in both cases of ½ inch inside diameter and 12 inches long, 1½ inch at each end being clamped in the graphite contact block. The carbon tubes are molded, of $\frac{15}{16}$ inch O. D. These gave good results only after the furnace had been heated two or three times, being allowed to cool and the tube cleaned after each heat. The first heating gave off considerable water vapor, also smoke from the constituents of the binding material of the carbon tube. The latter formed a slag at the ends of the tube, almost closing them, so that nothing further could be done until the chamber was opened and the slag cleared away. A strong impurity spectrum was also given, especially of sodium and aluminum. After the second heat there was much less trouble from these sources, and a number of very satisfactory runs were made with these tubes. A further troublesome feature of the carbon tubes is the fact that after a run at a high temperature, the carbon was thoroughly graphitized, making a considerable change in the resistance of the tubes.

Acheson graphite has given better satisfaction in many respects as a material for tubes. There is no appreciable water vapor given off, no slag formed, the material remains apparently unchanged, and the disturbance from impurities in the graphite is very small. The tubes were bored out and turned to $\frac{23}{32}$ inch O. D.

With both the carbon and graphite tubes, the ends of the tubes and also the holes in the graphite blocks for the tube and for the copper electrodes were thoroughly rubbed with powdered Acheson graphite, grade 1310, which filled the pores of the surfaces and greatly improved the contacts.

Pressure chamber.—The steel chamber to contain the cartridge described in the foregoing is shown in each of the photographs, Figs. 1 and 2, Plate XLIII. The length of the chamber without the heads is 24 inches, the internal diameter 8 inches, the walls having a ruling thickness of $1\frac{1}{2}$ inch, thickened at the ends with flanges 3 inches thick and 2 inches wide. In each of these flanges there are twelve steel bolts of $1\frac{1}{4}$ inch diameter to hold the heads. The head to which the cartridge is attached contains, besides the insulated bushings for the passage of the electrode tubes, a bronze window holder which screws into the center of the head and is provided with a high-pressure glass window in the form of a truncated cone with large end inside, the metal around the window being cooled with a special water jacket. For the work thus far, which has been done with the chamber pumped out, a piece of plate glass has been cemented on the outside of the window holder. The second head has a similar window holder and contains in addition two holes into which fit inlet and outlet pipes for gases and the connections for the high-pressure apparatus. The chamber has been tested to stand a working pressure of 200 atmospheres.

The steel chamber requires efficient water cooling, which is provided for by riveting a cylinder of galvanized sheet iron to the end flanges, allowing the space between them to be filled with water. The water enters below at one end of the jacket and leaves above at the other end.

Current supply.—The current is taken from a 50 K. W. transformer, fed with 2000 volts and giving 5, 10, 20, and 30 volts in the secondary. No regulating resistance is used, the different voltages being used for different temperatures of the furnace, and the voltage is put directly on the furnace tube with as little loss in the connections as possible.

Operation of furnace.—The furnace chamber, whose total weight is over 600 lbs., lies in a rack of cast iron, which rests in turn on the planed ring of an iron plate imbedded in the top of a masonry pier. The rack is centered by a pivot in the bed-plate, and may thus be turned in a horizontal plane to any desired angle. To remove the cartridge from the pressure chamber, the head to which the cartridge is attached is clamped firmly in the carriage shown to the right in the photograph, Plate XLIII, Fig. 2. This is a wooden ring mounted on a base provided with casters. The carriage is then rolled back on a table prepared for it, drawing the head horizontally off the bolts and with it the cartridge. The latter when drawn clear of the chamber is supported by a wooden stand on the table. The graphite blocks, resistance tube, and jacketing material are then placed in position in the open, where all of the parts can easily be put in correct adjustment. The substance to be vaporized is placed in the resistance tube and the cartridge returned to the chamber. The furnace is then turned back into position so that the two windows and the furnace tube in line with them are pointing toward the mirror above the slit of the large Littrow spectrograph,[1] in which position the heavy copper bars from the transformer connections fit into place on the ends of the copper pipe electrodes.

When the furnace is in position, if a run in vacuum is desired, the air is removed by means of a Geryk pump, the water is turned on through the several jackets, and the closing of a primary switch causes the current to pass.

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[1] See *Contributions from the Mount Wilson Solar Observatory*, No. 27.

Optical arrangement.—As has been noted, the furnace allows the spectrum of the substance vaporized in the resistance tube to be observed to equal advantage from either end. The Littrow grating spectrograph is usually used with the lens at the 13-foot focus. The light passes through a lens to a mirror which reflects it vertically to the slit. An image of the interior of the tube is thus formed on the slit, the middle portion of the length of the tube being in the sharpest focus. The image is made about the same size as the object and the slit is chosen of such length that only the light from the center of the image passes through, the image of the white-hot walls and of any solid matter in the tube being entirely cut out.

The comparison arc for the identification of lines is placed directly back of the furnace so that its light passes through the furnace tube and gives an image slightly out of focus on the slit if the same condensing lens is used. The proper position of the lens for the furnace tube being known, the adjustment of the image of the tube on the slit may be made by means of the light from the arc, so that all is in readiness for an exposure when the furnace is turned on.

The window at the other end of the furnace may be used to photograph with a prism spectrograph on a movable table, enabling a series of short exposures to be made simultaneously with the longer exposures required by the Littrow; or it may be used to watch the condition of the spectrum by means of a direct-vision spectroscope, enabling the exposures to be begun and ended at the proper time. A third use is for temperature measurements with the Wanner pyrometer during the progress of an exposure with the Littrow spectrograph.

Temperature measurements.—A Wanner pyrometer was used to measure the temperature of the hottest part of the furnace tube. This instrument has a Reichsanstalt calibration, and judging by the good agreement of its readings with and without the dark glass, is highly reliable. The measurements so far taken have been for the purpose of showing the temperatures corresponding to a certain voltage used on the furnace when a given tube was employed. Temperature measurements have not been made when a spectrum was being photographed, as the small window in the furnace head does not allow satisfactory temperature measurements to be made without a bright background such as a graphite plug placed in the central part of the tube. For this reason, special runs of the furnace were made for the pyrometer measurements, reproducing as nearly as possible the conditions under which a certain spectrum was observed. These observations have given results sufficiently concordant among themselves to give a reliable value for the approximate temperature corresponding to each voltage on the furnace. Thus with graphite tubes the following measurements were obtained:

Volts	Degrees C.	Number of Observations
5	1700–1800	4
10	2400–2500	4
20	2850–2950	2
30	3015	1

For the carbon tubes a lower series of temperatures was obtained, 1650°, 2570°, and 2770° being found from one set of readings for 10, 20, and 30 volts respectively.

These temperatures were measured for a certain length and size of tube and would of course vary if any of the dimensions were changed. They are given here merely to show the range of temperatures available in the work already done. Each set of observations was made for a different run of the furnace with a different tube, mounted in as nearly the same way as possible. The temperature was taken in each case after the current had passed long enough to bring the tube to a fairly steady condition, attained only after the jacketing material had become highly heated; and at the lower voltages some increase over the above temperatures could be obtained by prolonging the run.

It will be noted that the use of 30 volts does not give a proportional increase in temperature over 20 volts and that the highest temperature obtained with the graphite tube (which would probably have been increased only slightly, if at all, by the use of a still higher voltage) is considerably below the temperature of the positive pole of the carbon arc, measured by Waidner and Burgess[1] with the

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[1] *Bulletin, Bureau of Standards,* Vol. I, pp. 109–124.

Wanner pyrometer as about 3400° C. With the carbon tubes, the graphitizing of the material, which occurred after a short run at 20 volts and thereby lowered the resistance of the tube, was doubtless in some measure responsible for this; but in the case of the graphite tubes the material appears to remain unchanged. In the light of the data thus far obtained, it seems fair to ascribe this condition to the lively vaporization of the carbon (or graphite) which begins at about 2500° C. and becomes so vigorous at 2800° C. that the life of the thin graphite tube is very short when used at 20 and 30 volts. The carbon spectrum was regularly obtained with the graphite tubes at the 10-volt temperature and became very intense at the higher voltages. We have thus conclusive evidence that the vaporizing point of carbon is much below the temperature of the hottest part of the carbon arc, making it probable that the high temperature of the positive terminal is due to a superheating caused by a bombardment of this pole by particles impelled by the electric forces present in the arc.

It has been noted that a graphite plug in the middle of the tube was used when making a pyrometer measurement, in order to provide an incandescent surface at which to direct the instrument. It should give measurements of the same accuracy if the pyrometer were directed at the inner surface of the incandescent tube, and a measurement was made to test this with the bronze window holder removed, giving an opening $1\frac{3}{4}$ inch in diameter in the steel head, which was covered by a piece of plate glass. With this aperture, the pyrometer was directed alternately at the plug and at the adjacent wall of the tube, and the readings were practically the same, showing that the measurements made with the plug in the tube were approximately correct for the wall in the middle portion. When the tube is unobstructed and filled with vapor from any substance placed in it there is of course more or less of a temperature gradient between the wall and the vapor in the center.

SPECTROSCOPIC RESULTS

A series of photographs has been made of the spectra of iron, chromium, titanium, and vanadium with the Littrow spectrograph at its 13-foot focus, using the first order of a plane grating 5 inches

TITANIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4256.18	5	3	4512.88	36	15
4260.91	8	6	4518.18	38	15
4263.28	17	9	4522.97	40	15
4270.30	28	6	4527.48	36	18
4274.73	34	18	4533.42	40	21
4276.55	7	6	4534.97	40	18
4281.49	7	9	4536.25	44	33
4282.85	14	12	4544.83	38	15
4285.15	8	6	4548.93	38	15
4286.15	34	12	4552.62	42	15
4287.55	28	12	4555.64	38	15
4290.07	31	12	4558.28	3	6
4291.32	28	15	4563.60	34	12
4294.28	22	9	4590.11	6	6
4295.91	28	12	4617.41	40	15
4298.82	36	18	4623.24	34	15
4302.08	38	21	4629.47	17	15
4306.07	38	21	4639.83	34	24
4308.64	34	9	4645.36	10	12
4314.95	36	18	4650.16	8	9
4318.83	13	9	4656.60	36	18
4321.82	8	6	4667.76	38	18
4325.30	8	9	4675.27	6	15
4379.40	6	18	4682.08	39	21
4384.85	36	12	4691.50	19	15
4394.04	9	3	4698.94	18	15
4395.17	36	15	4710.34	12	18
4399.92	9	3	4715.46	3	18
4404.42	26	15	4723.32	6	12
4414.29	10	12	4731.33	4	9
4417.88	15	9	4742.94	13	6
4421.92	7	12	4758.30	24	9
4423.00	8	15	4759.44	26	12
4426.24	9	15	4778.44	5	3
4427.28	38	18	4781.91	4	12
4430.19	7	9	4792.65	5	3
4434.15	14	15	4799.95	6	6
4436.75	5	6	4805.25	8	9
4440.49	9	6	4820.56	10	15
4443.97	38	12	4841.00	22	15
4449.32	36	15	4848.62	3	6
4451.07	30	12	4856.18	12	9
4453.48	38	18	4868.44	8	9
4455.48	36	15	4870.28	10	12
4457.59	40	21	4885.25	15	15
4463.70	9	12	4900.08	14	12
4465.96	20	12	4913.76	10	15
4471.40	22	15	4419.99	2	6
4475.00	8	12	4921.90	4	9
4480.72	8	3	4928.50	3	9
4481.41	35	12	4973.25	2	6
4482.84	8	9	4975.52	3	9
4489.24	19	9	4978.39	3	9
4496.33	22	18	4981.91	40	21

TITANIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4989.33	3	9	5210.55	40	30
4991.24	40	21	5219.88	4	21
4997.26	3	15	5224.71	8	18
4999.67	40	21	5238.77	3	18
5001.16	5	12	5246.75	1	9
5007.42	38	18	5251.14	4	18
5009.81	2	15	5266.20	6	18
5013.45	5	9	5283.63	6	9
5014.40	40	21	5295.95	5	15
5016.32	14	18	5297.42	5	9
5020.17	20	18	5298.61	3	12
5023.02	18	18	5369.81	7	18
5025.00	15	15	5397.28	8	24
5036.10 }	20	12	5404.25	5	18
5036.65 }			5409.81	8	24
5038.55	16	12	5426.48	2	24
5040.12	24	15	5429.37	4	21
5043.77	2	15	5436.93	2	12
5045.58	2	18	5438.53	2	9
5053.06	2	12	5446.80	7	27
5064.82	30	21	5449.40	4	6
5087.24	3	15	5453.88	7	24
5113.64	4	15	5460.72	7	24
5120.60	7	12	5471.43	6	12
5145.62	8	15	5474.43	9	18
5147.63	7	21	5477.92	12	15
5152.36	6	21	5481.64	10	21
5173.94	34	27	5488.44	8	12
5193.15	39	27	5490.38	16	21
5194.25	2	6	5504.10	14	9
5206.30	8	21	5512.72	38	27
5208.08	8	18	5514.58	40	42

VANADIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4090.70	38	15	4128.25	44	18
4092.83	42	15	4132.13	43	18
4095.64	32	15	4134.61	42	18
4099.93	33	12	4143.02	9	12
4102.32	26	15	4160.57	11	15
4105.32	42	15	4180.99	26	21
4109.94	42	15	4183.59	11	12
4111.92	44	18	4191.70	14	15
4113.65	9	6	4194.17	12	15
4115.32	42	15	4209.98	15	21
4116.64	40	24	4216.52	21	15
4119.58	15	6	4232.62	16	9
4121.13	9	6	4234.12	14	15
4123.65	44	15	4235.90	8	6

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4251.45	6	9	4469.88	40	15
4257.53	5	6	4474.89	26	15
4259.46	6	15	4480.20	8	18
4265.28	5	6	4489.06	42	24
4268.78	40	15	4491.35	10	3
4271.71	40	15	4496.26	11	27
4277.12	35	9	4502.12	15	15
4283.06	4	9	4506.41	6	6
4284.19	34	12	4514.36	9	3
4286.57	5	15	4517.77	5	27
4287.97	4	15	4524.38	21	6
4291.97	23	18	4529.47	16	6
4293.25	3	9	4530.97	6	6
4296.28	19	18	4537.84	6	3
4306.35	22	27	4540.18	6	9
4307.33	20	15	4545.57	42	12
4309.95	22	27	4552.05	4	24
4330.18	42	24	4554.21	6	24
4332.98	41	21	4560.90	38	12
4341.15	43	24	4570.60	7	6
4353.02	44	27	4571.96	35	12
4356.10	13	21	4577.36	42	33
4363.48	6	15	4579.38	5	9
4368.25	19	18	4580.57	42	30
4379.38	48	39	4586.54	43	45
4384.07	42	6	4591.39	17	6
4384.87	45	33	4594.27	44	48
4390.13	47	30	4600.34	3	3
4392.24	8	18	4606.33	18	27
4395.40	44	30	4607.40	2	6
4400.74	43	24	4611.10	5	9
4405.20	30	15	4619.97	38	27
4406.80	45	24	4624.62	10	18
4407.85	44	21	4626.67	9	15
4408.36	44	33	4635.35	16	36
4412.30	18	24	4640.25	8	21
4416.63	42	27	4640.92	6	12
4420.08	19	21	4646.59	17	21
4421.73	41	27	4666.33	4	24
4423.41	10	15	4670.66	26	21
4426.17	42	39	4684.64	3	6
4428.68	40	24	4687.10	5	15
4429.95	32	33	4710.74	9	24
4434.80	11	6	4717.85	7	9
4436.31	42	27	4721.70	6	9
4438.02	40	30	4723.06	7	9
4441.88	44	30	4742.79	4	6
4444.40	42	27	4766.80	8	6
4449.77	8	15	4776.54	14	9
4452.19	40	21	4784.65	3	15
4457.65	43	42	4786.70	12	6
4459.93 }	48	36	4793.10	2	3
4460.46 }			4797.07	15	6
4462.56	41	18	4799.94	4	15

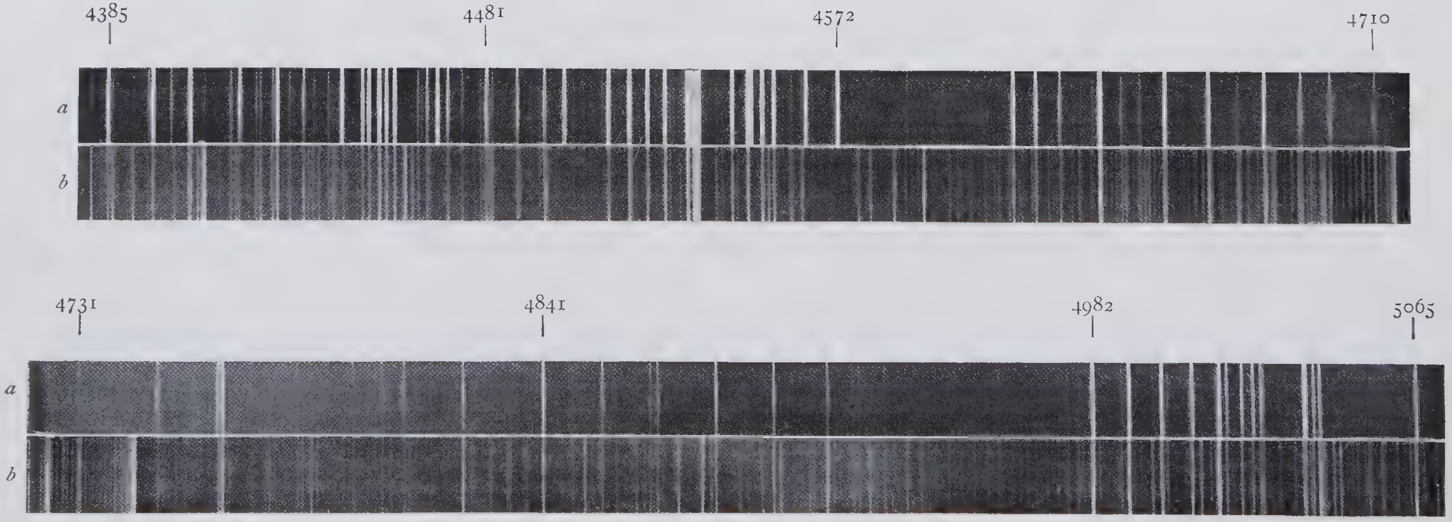
VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4807.70	18	6	5128.71	5	18
4827.62	28	30	5138.58	4	9
4832.59	26	24	5139.74	3	9
4833.17	26	21	5148.95	3	21
4851.65	40	27	5159.56	3	15
4864.93	39	21	5193.18	6	21
4875.66	41	21	5195.01	7	6
4881.75	42	24	5234.31	7	6
4891.81	3	9	5402.17	12	6
4900.84	4	9	5415.51	17	6
4904.59	7	6	5418.33	3	9
4925.83	5	6	5434.43	6	18
4932.24	2	6	5437.93	2	9
5014.83	3	18	5443.50	1	30
5064.83	2	9	5488.18	17	12
5105.37	6	6	5490.22	5	18

in length with 14,438 lines to the inch. The iron spectrum has been photographed for the region from λ 3700 to λ 6700. The plates thus far taken for the other substances extend only from λ 4000 to λ 5500. Each spectrum was obtained for at least two different temperatures, an exposure being made first with a low voltage on the furnace and then another with a higher voltage, the current being broken for only a few seconds, so that the higher voltage started with the tube and jacketing highly heated from the previous run, and the second exposure was made after a much higher temperature had been established. The exposure times varied with the substance, temperature, and region of spectrum, from one minute at the highest temperatures to 30 minutes for a spectrum barely visible in the direct-vision spectroscope. Ten minutes were usually ample for any spectrum at 2500° C. or higher. The change of temperature during these exposures was not large, and could be kept nearly constant when desired by watching selected parts of the spectrum, especially the carbon flutings, in the visual spectroscope and breaking the current for a few seconds when these became too bright.

It is not the purpose of the present paper to discuss the effects of different temperatures upon spectra; so that in the foregoing tables only a comparison of the arc and furnace spectra of titanium and vanadium is given, with the object of showing the richness of the furnace spectra as compared with the arc and to give a general view

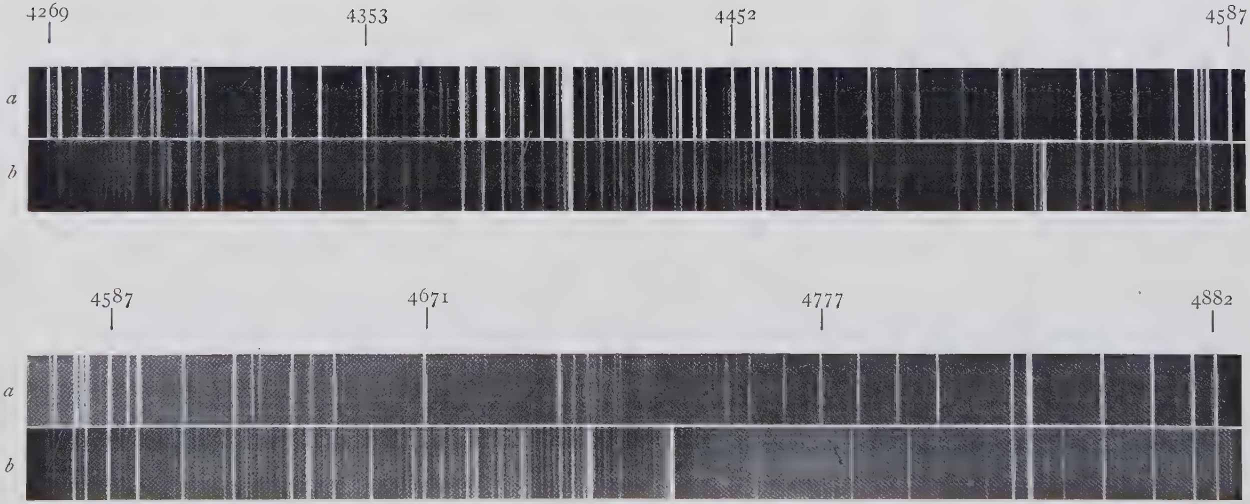
PLATE XLIV



Spectrum of Titanium

(*a*) In Carbon Arc; (*b*) In Electric Furnace

PLATE XLV



Spectrum of Vanadium

(*a*) In Carbon Arc; (*b*) In Electric Furnace of the relative intensities of lines in the two sources, as these spectra have not heretofore been obtained, to the writer's knowledge, by non-electrical methods. These furnace spectra were among the first photographed and were obtained with carbon tubes at about 2700°–2800° C. The arc spectrum was obtained on the same kind of plate (Cramer Isochromatic) with all optical arrangements the same.

The intensities of lines for both arc and furnace spectra were measured by means of a photographic scale made with the Littrow spectrograph by illuminating the slit with a constant voltage incandescent lamp and photographing the direct reflection from the grating with exposures ranging from 1 to 40. This gave a fairly satisfactory scale as regards gradation in blackness. The change in width of the lines of the scale with exposure time was also measured and a curve plotted to show this variation. This scale was placed in a special holder on a Zeiss spectrocomparator, so that when a spectrum plate was mounted on the moving carriage any line of the spectrum could be brought into the field of the eyepiece opposite the lines of the scale, giving, except for overexposed and reversed lines, a good measure of the intensity by selecting the line of the scale having the same blackness as the spectrum line. If the spectrum line was widened, this was considered in the final estimate of its intensity. Lines of intensity greater than 40 were estimated as closely as possible by extrapolation.

After the tables for arc and furnace were prepared, all of the intensities of furnace lines were multiplied by 3, which gave the spectrum as a whole about the same strength as that of the arc and rendered the relative differences more distinct. Although this proceeding is open to objection from the photometric point of view, it serves well for the rough comparison aimed at in these tables, where the differences in intensity are usually large.

Photographs of the arc and furnace spectra are reproduced in Plates XLIV and XLV for a part of the region covered by the tables of titanium and vanadium lines. Each furnace spectrum shows the spectrum of the other element as an impurity. These photographs, considered in connection with the tables, offer material which may be discussed under the following heads:

1. The question of temperature radiation. There is nothing to

indicate that temperature was not the sole and sufficient agent in producing these spectra. Electrical action, other than the ionization at a heated surface, was entirely excluded, no arc of any sort being present. As to chemical action, the small residue of air in the pumped-out chamber should have had its oxygen consumed long before the metal in the tube reached its vaporizing point, and if this were not the case, it is scarcely conceivable that enough could have reached the substance at the middle of the white-hot tube to give the vigorous radiation observed as long as a trace of the metal remained. To be sure, some impurities are contained in the material of the carbon tubes; but the tubes of Acheson graphite, containing extremely little foreign matter, were fully as efficient in giving the spectra of the substances placed in them. The spectroscopic evidence on this point is the fact that titanium gives a pure line spectrum, with no trace of the flutings given in the flame of the arc burning in air and generally ascribed to the oxide.

2. The number of lines given by the furnace as compared to the arc. For titanium the rather strong arc photograph gives 31 lines of intensity 3 or higher (1 indicating a line barely visible on the plate) which do not appear on the furnace plate for this region (λ 4250 to λ 5500), the furnace plate thus showing 85 per cent. of the arc lines. For vanadium, the number is relatively smaller, 73 per cent. of the arc lines being given by the furnace from λ 4100 to λ 5500. Longer exposure with the furnace would doubtless have brought out more of the weak lines, as none of the furnace lines attained maximum intensity.

3. The temperatures at which the carbon flutings appear and reach high intensity have been given. The band at λ 4737 may be seen in the reproductions of both the titanium and vanadium furnace spectra. This and the band at λ 5165 are easily obtained of considerable intensity. The cyanogen bands at λ 3883 and λ 4216 also appear, but faintly on account of the small supply of nitrogen.

4. Mention may be made here of the behavior of the "enhanced lines," those given relatively strong in the electric spark as compared to the arc. Eleven of the enhanced lines of titanium given by H. M. Reese[1] appear in the table of titanium furnace lines, and with one exception

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[1] *Astrophysical Journal*, **19**, 322, 1904.

are relatively much weaker in the furnace that in the arc. Five enhanced lines are among the 31 arc lines not found on the furnace plate, the two strongest in this list, λ 4501.43 and λ 4572.15, being given by Reese as enhanced in the ratio 9 to 5. A full consideration of this interesting point, together with a study of the enhanced lines of iron, will be given when tables showing the effects of different furnace temperatures upon the several spectra are published.

5. An examination of the tables for both vanadium and titanium shows that generally the lines of shorter wave-length are much stronger in the arc than in the furnace; while in the green region the furnace lines are as a rule relatively stronger. As these lists of intensities for arc and furnace were made up quite independently, the showing made when they are placed side by side is striking evidence of a shift of maximum in the spectrum due to a temperature difference in the two sources.

MOUNT WILSON SOLAR OBSERVATORY
August 20, 1908

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ANOMALOUS REFRACTION PHENOMENA INVESTIGATED WITH THE SPECTROHELIOGRAPH

By W. H. JULIUS

According to the current interpretation of spectroheliograph results, *dark* flocculi indicate regions on the sun where the special gas, a line of which is used, exists in such conditions of density and temperature, that it strongly absorbs the light coming from deeper layers; whereas *bright* flocculi show us regions where, in consequence of higher temperature or chemical or electrical causes, the radiation of the gas exceeds its absorbing effect.

In a paper,[1] read before the Royal Academy of Amsterdam, in September 1904, I proposed an entirely different explanation of the same phenomena. A first attempt has there been made to account for the peculiar distribution of the light in photographs, secured with the spectroheliograph, by simply considering the anomalous refraction which waves from the vicinity of the absorption lines must suffer when passing through an absorbing medium, the density of which is not perfectly uniform.

If it proves possible to explain the observed facts on this basis, we shall be able to dispense with the assumption of any very marked differences as to the absorbing and emitting conditions of a certain gas or vapor in contiguous regions on the sun. Moreover, we then *might* assume the constituents of the solar atmosphere to be thoroughly mixed, their proportions in the mixture only varying with the distance from the sun's center.

That our interpretation does not presuppose the separate existence of cloudlike masses of calcium or iron vapor or of hydrogen, looks like a simplification and, therefore, an advantage; but even if one were compelled, by other considerations, still to believe in the real existence of such separate luminous or dark accumulations of certain substances, it would nevertheless be necessary to consider the effect which anomalous dispersion in those masses must have on the appearances revealed by the spectroheliograph.

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[1] *Astrophysical Journal*, **21**, 278, 1905.

Among the advantages I derived from a visit to the Mount Wilson Solar Observatory in August 1907 was the opportunity of using the 5-foot spectroheliograph for some experiments on anomalous refraction.

It was expected that when light, coming from a source with a continuous spectrum, traverses a space in which sodium vapor is unequally distributed, particulars about the distribution would be revealed by the spectroheliograph through the *refracting* properties of the vapor, rather than through its absorbing and emitting power. This expectation could be put to the test.

As an equipment for the study of anomalous dispersion phenomena in sodium vapor, exactly similar to the one described in my paper on "Arbitrary Distribution of Light in Dispersion Bands,"[1] had already been secured for the Solar Observatory by Director Hale, the experiments were readily made, thanks to the laboratory facilities available on the mountain.

The apparatus consists of a wide nickel tube, 60 cm long, the middle part of which is placed in an electric furnace, while the projecting ends are cooled by jackets with flowing water. The tube contains a few grams of sodium, and is permanently connected to a Geryk pump to remove the air and the gases which escape from the sodium during the first stages of the heating process. An arrangement is provided by which density-gradients of various known directions and arbitrary magnitude may be produced in the sodium vapor.

Sunlight coming from the mirror M (Fig. 1) of the Snow telescope, which has a focal length of 60 feet, passes through the tube T on its way to the slit S of the spectroheliograph. The distance between T and S is about 560 cm. A lens L_1 gives an image of the sun near the middle of the tube T. P is a diaphragm, with an adjustable slit, of which the lens L_2 projects an image in the plane of the diaphragm Q. Just behind the latter is a lens L_3; in combination with L_2 this forms an image of a section of the tube in the plane of the slit S of the spectroheliograph. In this image (Fig. 2) the rectangular window

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[1] *Astrophysical Journal*, **25**, 95, 1907.

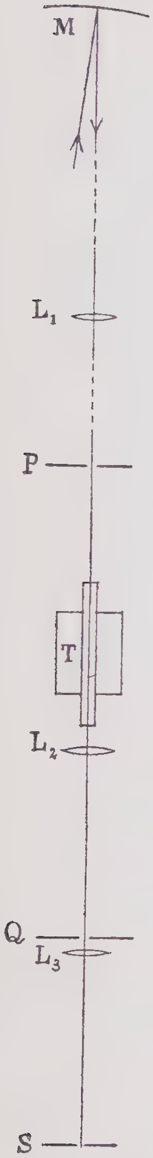

FIG. 1

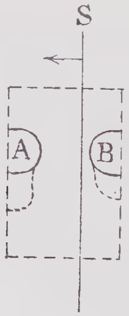

FIG. 2

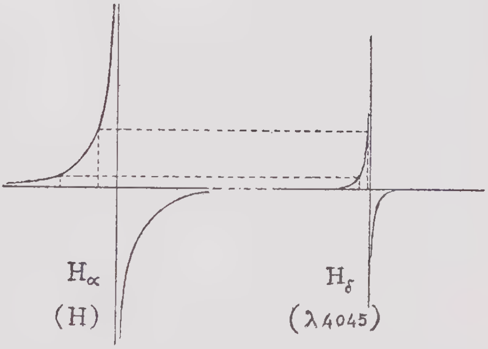

FIG. 3

of the caps of the tube[1] will of course come out with somewhat blurred edges, as only the middle section would show sharp. In *A* and *B* are projected the narrow nickel tubes for producing the required density-gradients. Their temperature may be varied at pleasure for this purpose by forcing an electric current or an air current through either of them. Cooling one of these tubes by an air current causes sodium vapor to condense on it; so in course of time drops of molten metal will hang on the tube, and fall off again.

When a photograph is made, the first slit *S* of the spectroheliograph moves across the image in the direction of the arrow, and at the same time the second or camera slit moves across the photographic plate.

Let us suppose the openings in *P* and *Q* (Fig. 1) to be so adjusted, that the image of the slit in *P* exactly coincides with the slit in *Q*. Then all of the light which passes through *P* and traverses the vapor along straight lines is transmitted by *Q*, and therefore contributes to the intensity of the image of the tube section. Waves, however, that deviate so much in the sodium vapor as to be intercepted by the screen *Q*, will be absent from the spectrum of the transmitted light.

If the furnace is slowly heated to 380° or 390°, the density of the vapor is pretty uniform in the middle part of the wide tube, and falls off toward the ends; but as the direction of the density-gradient nearly coincides with that of the beam of sunlight, even the waves subject to anomalous dispersion will hardly deviate from the straight path. The D lines in the spectroheliograph retain nearly their normal appearance. If now we blow air through the tube *B*, density-gradients are produced all around it in directions perpendicular to the axis of that tube. The D lines no longer show the same appearance throughout the field. In the spectrum of those parts of the field where perceptible gradients occur, the D lines then appear winged; they are indeed enveloped in *dispersion bands*. As the width of these bands depends on the magnitude of the gradient, it will, in our case, vary along the lines, and reach a maximum at the place in the spectrum which corresponds to the plane passing through the axes of the tubes *A* and *B*. With increasing distance between *S* and *B* (Fig. 2) the width of the bands will diminish.

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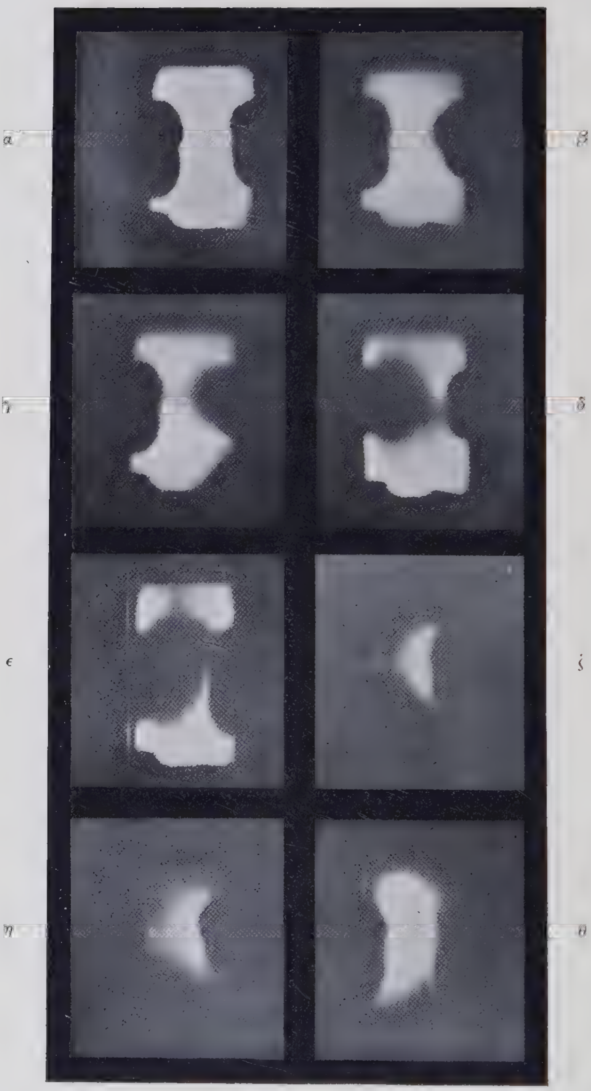
[1] Compare *Astrophysical Journal*, **25**, 97, 1907. Figs. 1, 2.

PLATE XLVI



Density-Gradients in Sodium Vapor as Shown by the Spectroheliograph

Let us consider the monochromatic images of the tube-section produced by the spectroheliograph if the camera slit is set at different distances from the D lines.

With the second slit at λ 5850, outside the region of the dispersion band of D_2, the illumination of the field is uniform (Plate XLVI, *a*); nothing is visible of the density-gradients existing around the cooled tube *B*, because light of this wave-length travels along straight lines through the vapor.

Proceeding to λ 5870, we still are at such a distance from D_2 that the value of $\frac{1-n}{\Delta}=R$ (n representing the index of refraction, Δ the density of the vapor) is moderate. Steep gradients of the density are required to make the rays deviate sufficiently to miss the slit in *Q*, and such gradients are only to be found very near the surface of the tube *B*. We therefore obtain the image β, in which *B* appears surrounded by a narrow dark region.

The third photograph, γ, was made with λ 5877. For these waves the expression $\frac{1-n}{\Delta}$ is greater than for λ 5870, so that smaller values of the gradient suffice to give the rays a perceptible incurvation. The result is a broader dark region all around *B*.[1]

The photographs δ and ϵ were secured with the second slit on λ 5881 and λ 5885 respectively. This time the tube *A* was cooled instead of *B*. We see the dark aureole grow as the wave-length we are using approaches $\lambda_{D_2}=5890$. Getting nearer still, the whole field would finally become dark.

Similar results are obtained if we approach D_1 from the side of the *greater* wave-lengths, thus using waves for which $\frac{n-1}{\Delta}$ has increasing values.

By a slight change in the arrangement of our experiment we may obtain the opposite effect, to wit, that merely rays suffering anomalous refraction enter the spectroheliograph, while the normally refracted light is prevented from reaching the slit. We have only to make the slit in *P* very wide, and to put a vertical bar (a match, for instance) in the middle of it, the image of which now falls exactly on the slit in *Q*. Under these circumstances light, issuing from the divided opening in *P*, can be transmitted by *Q* only if it has been deflected in the vapor. In this way the photographs ζ, η, θ were obtained, the second slit being set on λ 5884, λ 5886, λ 5888 respectively. If there had been no density-gradients, the whole field would have shown dark; the *bright* regions, however, now prove the existence of the gradients. When taking ζ and η, the tube *B*, and when taking θ, the tube *A*, was cooled.

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[1] In this image the lower right corner was cut off by a rubber tube accidentally crossing the path of the beam.

The following general statement is borne out by these experiments.

If an illuminated absorbing vapor is investigated by means of the spectroheliograph, and the camera slit of the instrument is set *on the edge* of a dispersion band, marked irregularities in the brightness of the field will only appear at those places in the image which correspond to regions with *large* density-gradients in the vapor. Setting the slit *nearer the middle* of the dispersion band, we shall get evidence, in the image, also of the regions with *smaller* gradients, etc. Particulars regarding the distribution of a vapor are thus clearly shown by the spectroheliograph through anomalous refraction, even in cases where the absorbing or emitting power of that medium would have failed to reveal its structure.

The bearing of these inferences on astrophysical phenomena may now be considered a little more closely.

Suppose we have a large mass of absorbing vapor of such average density that, if it were uniform, its absorption lines would appear rather narrow; and of such temperature, and condition of luminescence, that its emission lines are very faint. As soon as the density of this mass becomes irregular, some parts of it may give rise, when traversed by light from another source, to the appearance of dark or bright dispersion bands, greatly exceeding in width and strength its absorption or emission lines.

It is therefore *possible* that anomalous refraction plays a very important part in the production of those phenomena which the student of astrophysics observes with his spectroscope or spectroheliograph; we must inquire how far this is also *probable*.

One might be inclined to object, for instance, that in our experiments the use of a narrow and sharply limited source of light, placed at a fair distance behind the vapor, seemed to be a necessary condition for obtaining any marked dispersion effects, and that in the sun similar circumstances are very unlikely to prevail. Indeed, the body of the sun, whatever the nature of the photosphere may be, is a large incandescent mass, closely surrounded by the absorbing vapors, so that the "source of light," if considered from a point of the chromosphere, subtends a solid angle of nearly 2π. The reversing layer and the chromosphere have sometimes been compared to a thin, transparent layer of selectively absorbing varnish, covering a luminous (e.g., phosphorescent) globe: the photosphere. It seems very improbable that refraction in density-gradients of such a transparent envelope should be able to disturb to any perceptible degree the uniform brightness of that globe.

The comparison, however, is entirely misleading, because, so far, an essential relation between absolute size and density-gradients is overlooked in it. But if carried through properly, it will lead us to the opposite conclusion, namely, that refraction in the solar atmosphere must greatly alter the distribution of the light on the disk.

If we wish to form an image, on a reduced scale, of the sun considered as a refracting body, we have to reduce the radii of curvature of the rays in the same proportion as we do the diameter, for instance 10^{10} times (so as to make the diameter of the photosphere 14 cm).

By the general equation

$$\frac{d\Delta}{ds}=\frac{1}{R\rho}\text{[1]} \qquad (1)$$

we know that, for a given value of the refraction constant R, the radius of curvature ρ of a beam of light is inversely proportional to the density-gradient $\frac{d\Delta}{ds}$ in the direction toward the center of curvature. In our image, therefore, the density-gradients have to be taken 10^{10} times as great as they are in the sun.

Let us suppose that at a certain level in the solar atmosphere irregular density-gradients occur, that are of the same order of magnitude as the radial (vertical) density-gradient in our earth's atmosphere, viz., 16×10^{-10}.[1] At the corresponding points in our image we then have to put $\frac{d\Delta}{ds}=16$. If the layer of "varnish" were really traversed by many density-gradients of this order of magnitude, it would be very different from ordinary transparent varnish, and certainly be able to disturb the uniform brightness of the background, somewhat like a layer of glass beads or swollen sago grains. Even normally refracted waves would perceptibly deviate in an envelope of this kind. For if in our equation (1) we put $\frac{n-1}{\Delta}=R=0.5$ and $\frac{d\Delta}{ds}=16$, we get $\rho=0.125$ cm, so that the average curvature of such rays is already sufficient for producing sensible changes in the divergence of beams on their way through a shell not thicker than 0.1 cm.

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[1] *Astrophysical Journal*, **25**, 107, 1907.

Waves suffering anomalous refraction will of course be much more scattered by the same medium. Let us consider an absorbing substance which, at a certain level, occupies say only 1 per cent. of the solar atmosphere, taken as a perfect mixture. Its density-gradients will then be only $\frac{1}{100}$ of those of the mixture. The refraction constant, on the other hand, for waves near one of its absorption lines may attain values as high as 1000 or 2000. With $R=1600$ (observed in sodium vapor, *Astrophysical Journal*, **25**, 108, 1907) our equation (1) becomes

$$\frac{1}{100}\frac{d\Delta}{ds}=\frac{1}{1600\,\rho}\,.$$

In a level where in our image the irregular density-gradients of the envelope were supposed to have an average value $\frac{d\Delta}{ds}=16$, the equation gives

$$\rho=0.004\text{ cm.}$$

It is evident that under such circumstances rays may easily deviate 90 degrees and more in the thin shell of transparent matter covering our globe, and thus give rise to a very unequal distribution of the light in photographs of it, secured with the spectroheliograph.

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[1] The frequent occurrence of density-gradients nearly perpendicular to the radii of the sun is rendered more probable still since increasing evidence has been obtained by Professor Hale of the existence of solar vortices, in which the convection currents (especially in sun-spots) are sufficiently strong to produce magnetic splitting of absorption lines. (Cf. *Nature*, **78**, 368–370, Aug. 1908.)

This conclusion holds quite as well with regard to the real sun. It follows directly from our *only* assumption that in some level of the sun there exist irregular density-gradients comparable in magnitude with the vertical gradient in the earth's atmosphere. At lower levels greater gradients, at higher levels smaller gradients, may then be expected to prevail. As the validity of this assumption can hardly be doubted, we may infer that the existence of some important influence of anomalous dispersion on astrophysical phenomena is not merely possible, but *exceedingly probable*, in spite of the absence of narrow slits as sources of light.

Although we are free to admit that the phenomena observed with the spectroheliograph on the solar disk are in part due to absorption and selective radiation, dependent on various conditions of temperature or luminescence, we may nevertheless inquire into some consequences to which one is led if only the effects of refraction in a mixture of vapors are considered.

The composition of the solar atmosphere cannot be the same at all levels. As we get lower, the percentage of heavier molecules is likely to increase; but we should not presume too much as to the order in which the elements will come into evidence, on account of possible condensation, and because the pressure of radiation counteracts gravitation to a degree that depends on the size of the particles, and, therefore, on numerous unknown conditions prevailing in the sun.

Yet for each element a certain level must exist, in which its percentage in the mixture is a maximum. Accordingly, the refracting properties of successive layers will be governed by different elements. A photograph, made with the spectroheliograph in a hydrogen line, shows a structure which of course depends on the distribution of all the hydrogen present in the successive layers, but is chiefly determined by the density-gradients in a rather high level; whereas a photograph made with an equally strong iron line reveals especially the structure of lower regions. This explains the difference in character between iron and hydrogen plates.

It must be possible, on the other hand, to obtain almost identical photographs with different lines, provided they belong to the same element, or to elements that are most in evidence at about the same level of the sun; but then another condition has also to be fulfilled, viz., that the camera slit transmit rays of the same refrangibility in both cases. If, for instance, Fig. 3 represents the dispersion curve near $H\alpha$ and near $H\delta$, the width and the position of the camera slit ought to be so chosen as to let in only waves corresponding to parts of the curve inclosed between equal ordinates in the two dispersion bands.[1]

Recently it has been found by Hale and Ellerman that, while $H\beta$ and $H\gamma$ and $H\delta$ lines give very similar results, photographs with the much stronger $H\alpha$ line are widely different in some respects. Bright flocculi appear on these plates at points where no corresponding objects are shown by $H\delta$. Moreover, the dark $H\alpha$ flocculi, while showing a general agreement in position and form with those of $H\delta$, are stronger and more extensive. In some instances, however, small areas appear dark in $H\delta$ which are absent or fainter in $H\alpha$.[2]

Such differences seem to be of the same character as those observed between photographs made with the slit in the broad calcium bands H or K at various distances from the central line. They may find a similar explanation if we assume that the average rays used in the $H\alpha$ photographs were refracted to a higher degree than those used in the $H\delta$ photographs, but both by the same density-gradients. It is not improbable, therefore, that in the wings of $H\alpha$ waves may be selected so as to give spectroheliograph results closely resembling $H\delta$ plates.

That also lines of different elements may give very similar results with the spectroheliograph, is exemplified by the case of calcium and iron. Among the beautiful collection of photographs secured on Mount Wilson I saw several iron (λ 4045) plates resembling certain calcium (H_1) plates of the same daily series rather closely. As the atomic weights of calcium and iron are not so very different and their levels of maximum density therefore probably not far apart, the refraction caused by these elements may bring out the density-gradients of nearly the same layer of the solar atmosphere. It will do so by a similar distribution of the light in the two photographs—provided that rays of the same refrangibility are used in both cases. And this condition may be fulfilled by setting the camera slit on corresponding regions of the spectrum, in the manner illustrated by Fig. 3, if we imagine it now to bear on the calcium (H) line and the iron line.

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[1] Waves lying about symmetrically on either side of an absorption line, and answering the relation $n-1=1-n'$ between the indices of refraction n and n' of the medium for them, must give nearly the same spectroheliograph results on the greater part of the disk. This follows from a discussion of the various possibilities regarding the relative position of density-gradients and the source of light. Consequently an $H\delta$ plate, obtained with the camera slit centrally, so as to embrace the whole width of that rather narrow dispersion band, will scarcely differ, at first sight, from a photograph made with only one of the wings.

[2] *Memorie Soc. Spettroscopisti Italiani*, **37**, 99, 1908.

With a calcium and a hydrogen line such similarity could not be found.

Far more evidence will of course be required before we shall be able to decide whether or not anomalous dispersion is the principal agent in determining the flocculent appearance of the solar disk. Plates secured with many lines of various elements should be compared. The powerful 30-foot spectroheliograph of the "tower telescope" of Mount Wilson is excellently adapted for work of this kind, not only on account of its great dispersion, permitting the use of finer lines, but chiefly because it is provided with three camera slits, so that perfectly simultaneous photographs with different lines may be secured. By this arrangement, really comparable monochromatic pictures of the sun may be obtained, since the otherwise confusing influence of the variable refraction in our atmosphere is thus rendered harmless.

I feel greatly obliged to Professor George E. Hale for having procured me the opportunity of making an investigation at the Mount Wilson Solar Observatory, but more still for his keen and stimulating interest in the problems suggested by the application of the principle of anomalous refraction to astrophysics. I am also very much indebted to the kindness of Mr. F. Ellerman, Mr. W. S. Adams, and Dr. C. M. Olmsted for valuable information and assistance in connection with the inquiry here reported upon.

UTRECHT
August 1908

Contributions from the Mount Wilson Solar Observatory, No. 30
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ON THE PROBABLE EXISTENCE OF A MAGNETIC FIELD IN SUN-SPOTS[1]

By GEORGE E. HALE

The discovery of vortices surrounding sun-spots, which resulted from the use of the hydrogen line *Ha* for solar photography with spectroheliograph,[2] disclosed possibilities of research not previously foreseen. Photographs taken daily on Mount Wilson with this line suggest that all sun-spots are vortices, and provide material for a discussion of spot theories which will soon be undertaken. Revealing, as they do, the existence of definite currents and whirls in the solar atmosphere, they afford the requisite means of testing the operation in the sun of certain physical laws previously applied only to terrestrial phenomena. The present paper describes an attempt to enter one of the new fields of research opened by this recent work with the spectroheliograph.

ELECTRIC CONVECTION

In 1876 Rowland discovered that an electrically charged ebonite disk, when set into rapid rotation, produced a magnetic field, capable of deflecting a magnetic needle suspended just above the disk.[3] It thus appeared, in accordance with Maxwell's anticipation, that a rapidly moving charged body gives rise to just such effects as are caused by an electric current flowing through a wire. Rowland's whirling disk therefore corresponds to a short wire helix, within which a magnetic field is produced when a current is passed through it.

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[1] A preliminary note bearing the title, "Solar Vortices and the Zeeman Effect, was sent to *Nature* for publication June 30. A brief abstract of this note appeared in *Nature* for August 20, together with a very interesting paper by Professor Zeeman, who was kind enough to examine some copies of my photographs, taken with the rhomb and Nicol in June. My own note was subsequently printed in *Publications of the Astronomical Society of the Pacific*, **20**, 220, 1908.

[2] Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Rowland, "On the Magnetic Effect of Electric Convection," *American Journal of Science* (3), **15**, 30, 1878.

Recent studies of the discharge of electricity in gases prove that gases and vapors, when ionized by one of several means, contain electrically charged particles. Moreover, at high temperatures carbon and many other elements which occur in the sun emit negatively charged corpuscles in great numbers; the complementary positively charged particles must also be present, more or less completely separated from the negative corpuscles.[1] Thus electromagnetic disturbances on a vast scale may result from the rapid motions of charged particles produced by eruptions or other solar disturbances.

Soon after the discovery of the vortices associated with sun-spots, it occurred to me that if a preponderance of positive or negative ions or corpuscles could be supposed to exist in the rapidly revolving gases, a magnetic field, analogous to that observed by Rowland in the laboratory, should be the result. An equal number of positive and negative ions, when whirled in a vortex, would produce no resultant field,[2] since the effect of the positive charges would exactly offset that of the negative charges. But Thomson's statement regarding the possible copious emission of corpuscles by the photosphere, and the tendency of negative ions to separate themselves, by their greater velocity, from positive ions, led to the belief that the conditions necessary for the production of a magnetic field might be realized in the solar vortices.

Thanks to Zeeman's discovery of the effect of magnetism on radiation, it appeared that the detection of such a magnetic field should offer no great difficulty, provided it were sufficiently intense. When a luminous vapor is placed between the poles of a powerful magnet the lines of its spectrum, if observed along the lines of force, appear in most cases as doublets, having components circularly polarized in opposite directions. The distance between the components of a given doublet is directly proportional to the strength of the field. As different lines in the spectrum of the same element are affected in different degree, it follows that in a field of moderate strength many of the lines may be simply widened, while others, which are exceptionally sensitive, may be separated into doublets.

[1] J. J. Thomson, *Conduction of Electricity through Gases,* p. 165.

[2] Unless separated by centrifugal force, as suggested by Professor Nichols.

THE SUN-SPOT SPECTRUM

It has long been known that the spectrum of a sun-spot differs from the ordinary solar spectrum in several particulars. If, for example, we examine the iron lines in a spot, we find that some of them are more intense than in the solar spectrum, while others are weaker. Again, we perceive that many of the spot lines are widened, and that the degree of widening varies for different lines. Finally, if the observations are made with an instrument of high dispersion, it will be seen that some of the iron lines, which are single in the solar spectrum, are double in the spot spectrum. Such double lines were first seen by Young in 1892 with a large spectroscope attached to the 23-inch Princeton refractor. Walter M. Mitchell, who subsequently observed them with the same instrument, described the doublets as "reversals," which they closely resemble. Mitchell's papers contain a valuable series of observations of these "reversals" and other sun-spot phenomena.[1]

Our previous investigations in this field on Mount Wilson may be summarized as follows:

1. The application of photography to the study of sun-spot spectra. A Littrow or auto-collimating spectrograph of 18 feet (5.5 m) focal length, used with the Snow telescope, gave good results, and permitted a great number of spot lines and bands, not previously known, to be recorded.[2] On the completion of the tower telescope last autumn, these observations were continued with a vertical spectrograph of 30 feet (9.1 m) focal length.[3] Although the only grating available for work in the higher orders is a 4-inch (10 cm) Rowland, having 14,438 lines to the inch (567 to the mm), employed in my experiments in photographing sun-spot spectra at the Kenwood and Yerkes

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[1] Walter M. Mitchell, "Reversals in the Spectra of Sun-Spots," *Astrophysical Journal*, **19**, 357, 1904; "Researches in the Sun-Spot Spectrum, Region F to *a*," *ibid.*, **22**, 4, 1905; "Results of Solar Observations at Princeton, 1905–1906," *ibid.*, **24**, 78, 1906.

[2] Hale and Adams, "Photographic Observations of the Spectra of Sun-Spots," *Contributions from the Mount Wilson Solar Observatory*, No. 5; *Astrophysical Journal*, **23**, 11, 1906.

[3] Hale, "The Tower Telescope of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Observatories,[1] the results secured with this instrument are very satisfactory, greatly surpassing those obtained with the 18-foot spectrograph. They give the first photographic records of the "reversals" or doublets seen visually by Young and Mitchell, and reveal thousands of faint lines beyond the reach of visual observation.

2. The preparation of a photographic map of the sun-spot spectrum and a catalogue of all the lines. A preliminary map, consisting of 26 sections of 100 Ångströms each, covering the region λ 4600–7200, was prepared last year by Mr. Ellerman from negatives made with the 18-foot spectrograph, and supplied to visual observers taking part in the sun-spot work of the International Solar Union. A much better map, to be made from negatives obtained with the tower telescope and 30-foot spectrograph, will be ready, it is hoped, within a year. The catalogue of lines, which involves a great amount of measurement for the determination of wave-lengths, is well advanced, and one section has been published by Mr. Adams.[2]

3. The identification of the numerous lines which constitute the flutings in the spot spectrum. Photographs of the spectra of titanium oxide, magnesium hydride, and calcium hydride,[3] made in our laboratory by Dr. Olmsted, have furnished the material for this purpose. The measurement of the lines in these flutings is well advanced.

4. The interpretation of the change of the relative intensity of lines observed in passing from the solar spectrum to the spot spectrum. Investigations on the spectra of iron, manganese, chromium, titanium, vanadium, and other metals conspicuous in spots, made with the arc, spark, and flame, indicated that this change is due to a reduction of the temperature of the spot vapors.[4] Subsequent work with a new

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[1] Hale, "Solar Research at the Yerkes Observatory," *Astrophysical Journal*, **16**, 211, 1902.

[2] Adams, "Preliminary Catalogue of Lines Affected in Sun-Spots, Region λ 4000 to λ 4500," *Contributions from the Mount Wilson Solar Observatory*, No. 22; *Astrophysical Journal*, **27**, 45, 1908.

[3] Olmsted, "Sun-Spot Bands Which Appear in the Spectrum of a Calcium Arc Burning in the Presence of Hydrogen," *Contributions from the Mount Wilson Solar Observatory*, No. 21; *Astrophysical Journal*, **27**, 66, 1908.

[4] Hale, Adams, and Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906; Hale and Adams, "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 15; *Astrophysical Journal*, **25**, 75, 1907.

electric furnace by Dr. King,[1] the details of which have not yet been published, seems to leave little doubt that this explanation is correct. It is supported by the presence in the spot of compounds which appear to be dissociated at the higher temperature outside the spot, and by the resemblance of spot spectra to the spectra of red stars.[2]

While our investigations have thus furnished a plausible explanation of some of the characteristic phenomena of sun-spot spectra, the widening of lines and the presence of doublets are among the remaining peculiarities that demand consideration. As we have seen, however, these very peculiarities are precisely what would be expected if a magnetic field were present. Prompted by the theoretical considerations outlined above, and encouraged by their apparent agreement with the facts of observation, I decided to test the components of the spot doublets for evidences of circular polarization and to seek for other indications of the Zeeman effect.

METHOD OF OBSERVATION

The tower telescope forms an image of the sun, about 6.7 inches (17 cm) in diameter, on the slit of a vertical spectrograph, of 30 feet focal length. This instrument, to which reference has already been made, stands in a well with concrete walls, the grating being about 26½ feet (8 m) below the surface of the ground. The temperature at the bottom of the well is so constant that exposures of any desired length may be given, without danger of a shift of the lines resulting from expansion or contraction of the grating. A Fresnel rhomb and Nicol prism[3] are mounted above the slit, so that the light of the solar image passes through them. If the doublets in spots are produced by a magnetic field, the light of their components, circularly polarized in opposite directions, should be transformed by the rhomb into two plane polarized rays, differing 90° in phase. Thus, in a certain position of the Nicol, the light from the red component should be transmitted and that of the violet component cut off. When rotated 90° in azimuth, the Nicol should transmit the violet component and cut off the red component. Complete extinction of either component is hardly to be expected, because the light from the spot does not, in general, come exactly along the lines of force, and the doublets may therefore exhibit some traces of elliptical polarization. Moreover, the beam of sunlight undergoes two reflections on the silvered surfaces of the coelostat and second mirrors of the tower telescope, where elliptical polarization must again be introduced.[1] By setting the rhomb at the proper angle, the latter effect, which is not very large, can be almost wholly eliminated, but the former may play some part, even when the spot is at the center of the sun.

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[1] King, "An Electric Furnace for Spectroscopic Investigations, with Results for the Spectra of Titanium and Vanadium," *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] Hale and Adams, "Sun-Spot Lines in the Spectra of Red Stars," *Contributions from the Mount Wilson Solar Observatory*, No. 8; *Astrophysical Journal*, **23**, 400, 1906; Adams, "Sun-Spot Lines in the Spectrum of *Arcturus*," *Contributions from the Mount Wilson Solar Observatory*, No. 12; *Astrophysical Journal*, **24**, 69, 1906.

[3] Obtained for this purpose in 1905, when the idea of searching for the Zeeman effect in sun-spots had already occurred to me. A visual test of the spot lines for plane polarization, made with the 18-foot spectrograph in 1906, before we had photographed the doublets, gave negative results.

The light of the spot, after transmission through the rhomb and Nicol, comes to a focus in the plane of the slit. While photographing the spot spectrum the slit is covered, except at its central part, where a portion corresponding in length (from 1 to 2 mm) to the diameter of the umbra, receives the light. During the exposure, which may continue from a few minutes to over an hour, the image of the umbra is kept as nearly as possible central on the slit, any irregularities in the motion of the driving-clock being corrected by the observer. As the exposure for the spot spectrum is from five to twenty times as long as for the solar spectrum, it is evident that care must be taken to prevent light from regions outside the spot from entering the slit.

For a comparison spectrum sunlight is used, generally from a point in the solar image a short distance away from the spot, where none of the characteristic spot phenomena appear. During the exposure, that part of the slit which previously received the light of the umbra is covered, and sunlight admitted on either side. The light of the comparison spectrum passes through the rhomb and Nicol, both of which occupy the same positions as in the case of the spot. Care is taken to see that the grating is fully illuminated, both for the spot and comparison spectra, in all positions of the Nicol.

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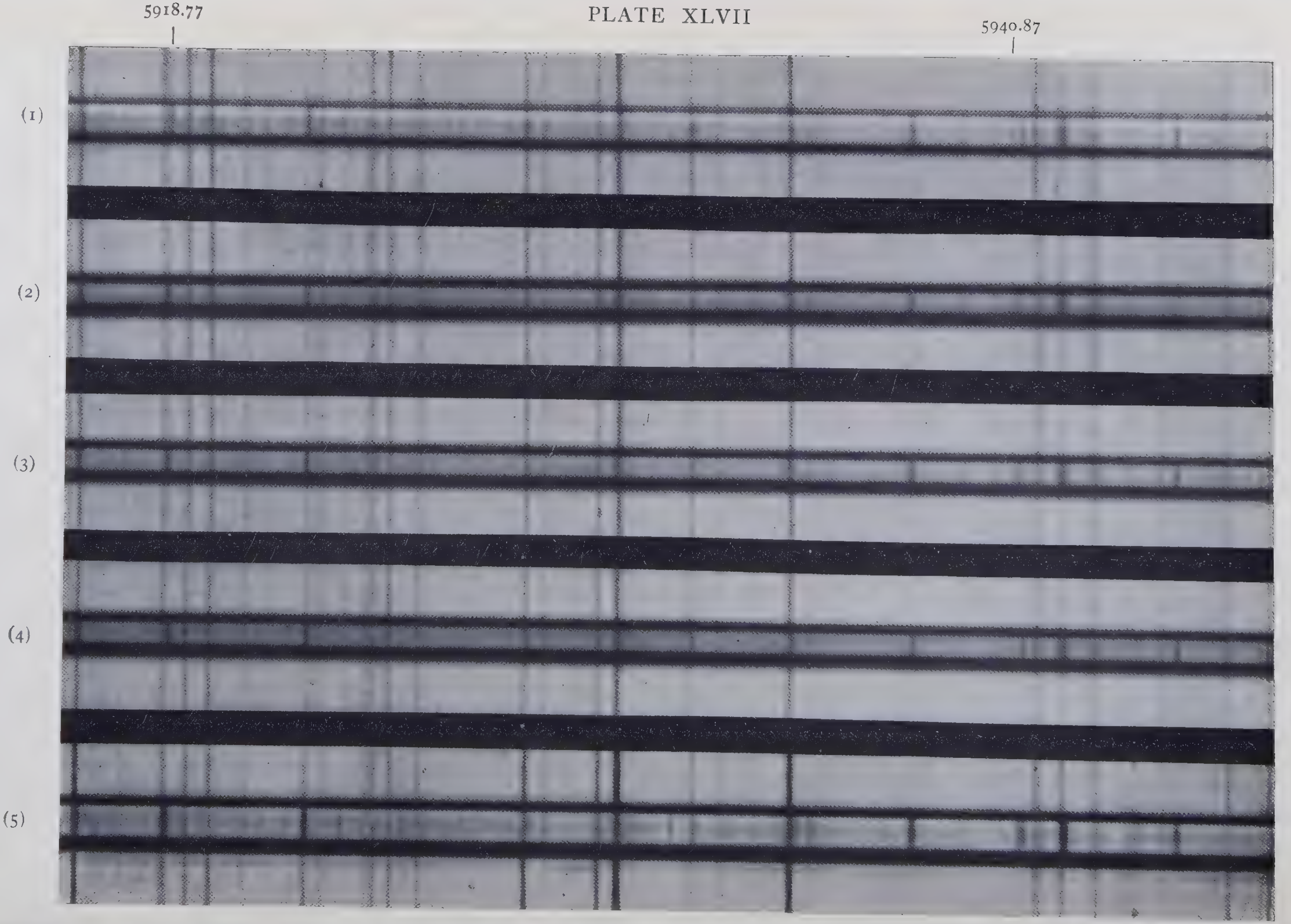
[1] A study of the elliptical polarization of these mirrors has been made by Dr. St. John.

PLATE XLVII



(1) Southern spot, showing red components of doublets. Nicol 20° W. (2) One umbra of northern spot, showing violet components of doublets.

CIRCULAR POLARIZATION ALONG THE LINES OF FORCE

My first observations were made on June 24, in the second order of the grating, but the results were not conclusive. On June 25 I obtained some good photographs, in the third order, of the region λ 6000–6200, using Seed's "Process" plates, sensitized for the red by Wallace's three-dye formula.[1] These clearly showed a reversal of the relative intensities of the components of spot doublets when the Nicol was turned through an angle of 90°. Moreover, many of the widened lines were shifted in position by rotation of the Nicol, indicating that light from the edges of these lines is circularly polarized in opposite directions. The displacements of the widened lines appeared to be precisely similar in character to those detected by Zeeman in his first observations of radiation in a magnetic field.

A series of photographs, made with the Nicol set at various angles, soon showed the two positions giving the maximum effect. At these positions the weaker components of the strongest doublets are not always completely cut off, but their intensities are greatly reduced. Sometimes hardly a trace of the weaker component remains, as may be seen in the case of the vanadium doublet at λ 5940.87 (Plate XLVII). In this plate No. 5 shows the doublet in the ordinary spot spectrum, photographed without the rhomb and Nicol. No. 4, from a photograph (T 190) made with the Nicol set at 61° E., shows only the red component of the doublet. No. 3 illustrates the effect of turning the Nicol 90°: only the violet component remains. Other spot lines in these photographs change in a similar way.

Photographs like these seemed to leave no doubt that the components of the spot doublets are circularly polarized in opposite directions. Since the only known means of transforming a single line into such a doublet is a strong magnetic field, it appeared probable that a sun-spot contains such a field, and that the widening and doubling of the lines in the spot spectrum result from this cause. But much remained to be done before the proof could be regarded as complete.

In the first place, it was necessary to make sure that the displacement of the lines other than doublets was not due to instrumental causes, such as a change in the illumination of the grating produced by rotating the Nicol. As already stated, care was always taken to see that the ruled surface was filled with light before making an exposure. Moreover, the magnitude of the displacement was much greater for some lines than for others, and the fact that the shifts were determined with respect to lines of the solar spectrum, whose light had traversed almost the same path as that of the spot in rhomb and Nicol, seemed to leave little room for doubt as to their true character. However, a rigorous test could be applied. The spot spectrum, as well as the solar comparison spectrum, is crossed by lines due to the absorption of water vapor and other gases in the earth's atmosphere. If a change of illumination due to the rotation of the Nicol were concerned, these lines should be displaced from their normal positions. But no such shifts were observed. Furthermore, it is known that the lines of most flutings are not affected by a magnetic field. Accordingly, the cyanogen fluting at λ 3883 was photographed in the spot spectrum, with the Nicol set in two positions 90° apart. Three lines in this fluting, which I have measured on negative T 132, made in the fourth order, show a mean displacement of 0.0004 Ångströms, with respect to the corresponding lines of the solar comparison spectrum. This quantity is well within the error of measurement.[1] We may therefore conclude that the Nicol displaces only those lines which show polarization phenomena.

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[1] *Astrophysical Journal*, **26**, 299, 1907.

While measuring this plate, and others taken in the more refrangible part of the spot spectrum, it was found that few of the lines in this region show large shifts. A group of doublets was encountered near λ 4400, the components of which are circularly polarized in opposite directions. In general, however, the shifts produced by rotating the Nicol decrease from the red toward the violet end of the spectrum.

Since this preliminary work I have made over two hundred photographs of spot spectra with polarizing apparatus before the slit. In addition to this collection of plates, numerous photographs of spot spectra, some taken with polarizing apparatus by Dr. St. John, and others made without Nicol or rhomb by Mr. Adams and myself, are available for study. These have been used for the investigation described in the following pages.

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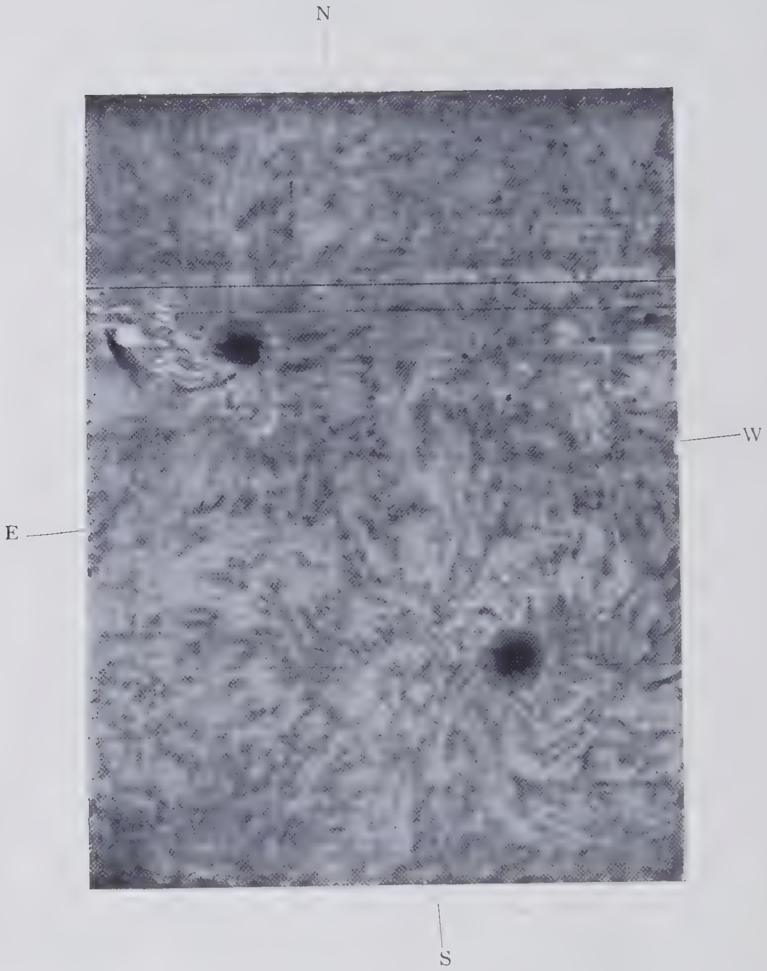
[1] The head and several lines of the titanium oxide fluting at λ 5598, which have since been measured by Mr. Adams, also show no displacement when the Nicol is rotated.

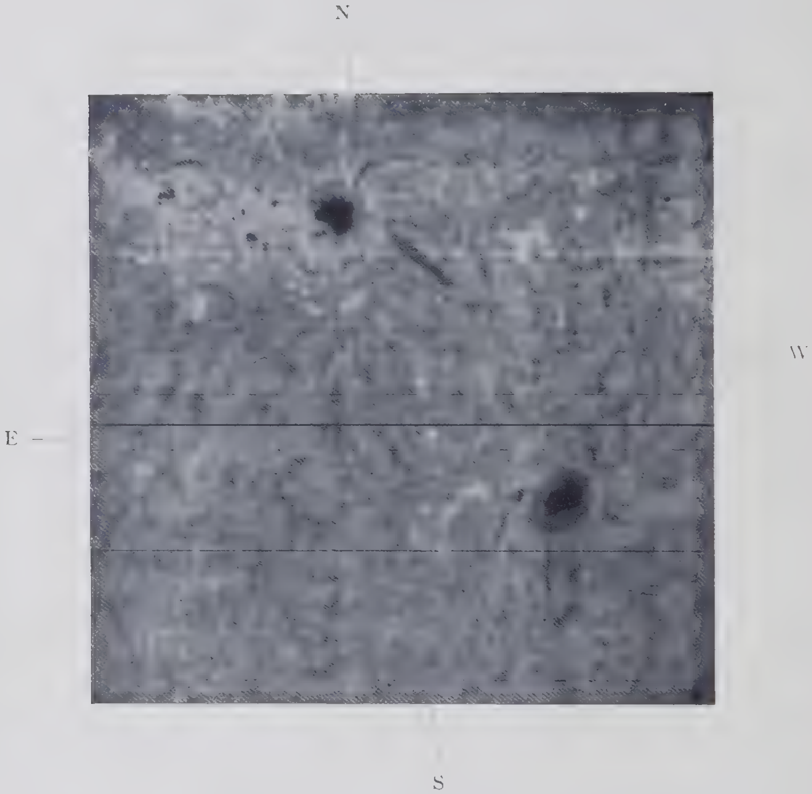
PLATE XLVIII



Sun-Spots and Hydrogen Flocculi, Showing Right- and Left-Handed Vortices

1908, September 9, 6^{h} 20^{m} A. M. Scale: Sun's Diameter=0.3 Meter

PLATE XLIX



Sun-Spots and Hydrogen Flocculi, Showing Right- and Left-Handed Vortices

1908, September 7, $6^h\ 20^m$ A. M. Scale: Sun's Diameter=0.3 Meter

REVERSED POLARITIES OF RIGHT- AND LEFT-HANDED VORTICES

A second test, which also bears upon the hypothesis that the field is produced by the revolution of electrically charged particles in the spot-vortex, may now be described. If a Nicol is set so as to cut off the violet component of a doublet observed along the lines of force of a magnetic field, reversal of the current will cause the red component to disappear and the violet component to become visible. Reversal of the direction of the current in a magnet corresponds to reversal of the direction of revolution in a solar vortex. If it could be shown, by an independent method, that in two sun-spot vortices the charged particles are revolving in opposite directions, the red components of the doublets should appear in the spectrum of one spot, and the violet components in that of the other, the position of the rhomb and Nicol remaining unchanged.

Fortunately, the spectroheliograph plates indicate the direction of revolution in the solar vortices. The vortices are constantly changing in appearance, and the stream lines are not always clearly defined. Plates XLVIII and XLIX are reproduced from photographs of the sun made by Mr. Ellerman with the 5-foot spectroheliograph on September 9 and 10. They show two spots, one in the northern, the other in the southern hemisphere, with vortices indicating revolution in opposite directions, if we may judge from the curvature of the stream lines.[1] Portions of the spectra of these spots, photographed by myself on September 9, are reproduced in Plate XLVII. No. 1 shows the spectrum of the southern spot, in which the direction of revolution was clockwise, taken with the Nicol set at 29° W. Only the red components of the doublets appear. The northern spot, in which the revolution was counter-clockwise, was then photographed (2). Although the Nicol and rhomb remained in the same position as before, the red components of the doublets are now cut off, while the violet ones are visible. During this exposure the slit was kept on the western umbra of the northern spot, which was divided into two parts by a bridge (not shown in the reproductions). Another exposure, with Nicol and rhomb as before, was then made on the eastern umbra of the same spot (3), with results similar to those obtained for the western umbra. For the final exposure (4) the slit was kept on the eastern umbra of the northern spot, and the Nicol rotated 90°. As was to be expected, the red components were brought into view, and the violet components extinguished. This spectrum is therefore precisely similar to that of the southern spot, which was taken with the Nicol in the reverse position.

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[1] Right- and left-handed vortices have also been found in the *same* hemisphere.

This result has been confirmed by other photographs, which indicate that the direction of the displacement always depends upon the direction of revolution in the vortex. If this relation is found by future observations to hold generally, we may conclude that the field is always produced by the revolution of particles carrying charges of like sign.

PLANE POLARIZATION ACROSS THE LINES OF FORCE

So far we have confined our attention to polarization phenomena observed along the lines of force. But it is well known that the doublets are, in general, transformed into triplets, when observed in a magnetic field at right angles to the lines of force. The components of the triplets are plane polarized, the central line in a plane at right angles to the plane of polarization of the side components. It should be possible to detect similar phenomena in spot spectra, if they are produced in a magnetic field.

It naturally happens that these spectra are most commonly observed when the spots are not very far removed from the center of the sun, because foreshortening near the limb reduces the umbra to a narrow strip difficult to keep on the slit. This may partially explain why our photographs of spot spectra, taken without polarization apparatus, show the doublets without a trace of a central component. But it does not account for the failure of the central line to appear in the spectra of spots well removed from the center. It is true that a few triplets occur in all of our spot spectra, such as λ 5781.97, λ 6064.85, and λ 6173.55. But these I have regarded as probable examples of an exceptional type of lines, observed in the laboratory as triplets along the lines of force. Mitchell records certain cases in which many spot doublets were seen as triplets,[1] but he also notes the existence of doublets in the spectra of spots near the limb.[2] In

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[1] *Astrophysical Journal*, **24**, 80, 1906.

[2] *Ibid.*, **19**, 357, 1906.

PLATE L

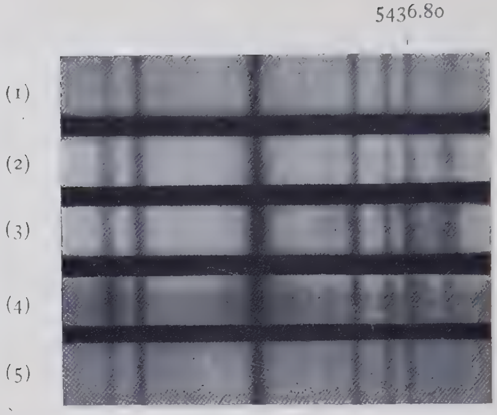

FIG. 1.—(1) and (5) Solar spectrum. (2) Spectrum of a spot near limb, Nicol 60° E. (3) Spectrum of a spot near limb, Nicol 60° W. (4) Spectrum of a spot near center, without rhomb or Nicol. Scale: 1 Ångström=6 mm.

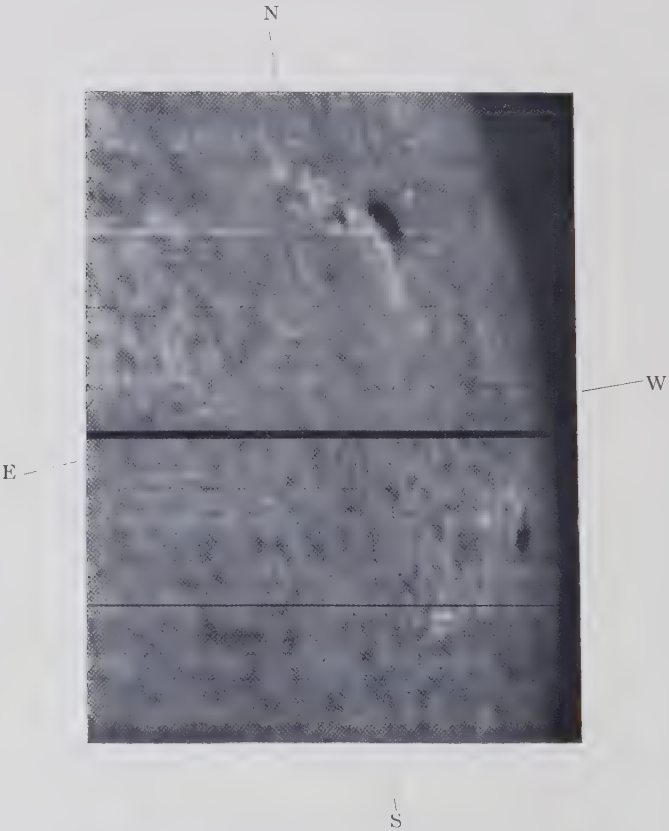

FIG. 2.—Spots near western limb, in which plane polarization of lines was observed.

1908, Sept. 14, $7^h\ 05^m$ A. M. Scale: Sun's Diameter=0.3 Meter.

one interesting observation described and illustrated by Mitchell, the lines appeared double across the umbra and one side of the penumbra, while on the other side of the penumbra they changed into triplets.[1] Since the beginning of my work on the Zeeman effect in the sun, there have been few opportunities to observe the spectra of spots near the limb. These I have utilized, not in attempting to photograph the triplets (which will be tried later), but in testing the polarization phenomena of the spot lines.

The rhomb was removed, and the Nicol employed alone. At right angles to the lines of force the Nicol, when in a certain position, should cut off the outer components of a triplet or the edges of a widened line. In another position, 90° distant, the central component should be extinguished, and the outer components or edges transmitted. Thus, in the second case, lines which are not too diffuse should be photographed as doublets, while in the first case the central component should appear alone.

Plate L reproduces some photographs of a spot near the west limb, made on September 14. The seeing was poor, and neither the $H\alpha$ image nor the spectra are sharply defined. In Fig. 1, Plate L, (1) and (5) represent the solar spectrum; (2) the spot spectrum, photographed with the Nicol set at 60° E.; (3) the spot spectrum, with Nicol set at 60° W.; (4) the same region of another spot spectrum, photographed near center of sun without Nicol.[2] At 60° E. the Nicol cuts out the central line of λ 5436.80, while at 60° W. it transmits this line and cuts off the side components. Other settings of the Nicol gave the following results, which appear on the same negative (T 200): 90° E., single; 30° E., double; 0°, single, but wide; 30° W., single, but wide. Other photographs, made in this and other regions of the spectrum, gave similar results, many lines being narrow in some positions of the Nicol and wide in others. Only one case (λ 5436.80) of undoubted doubling of the lines has been found. The short time available for work, under favorable atmospheric conditions, when a sufficiently large spot was near the limb, prevented the observations from being carried farther.

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[1] *Ibid.*, **24**, 80, 1906.

[2] This cut is very unsatisfactory, but a better one could not be obtained.

LABORATORY TESTS

If the widened lines and doublets in spot spectra are produced by a magnetic field, an equal degree of widening and an equal separation of the components of doublets should be found in the laboratory when the same lines are observed in a field of equal strength. As the necessary apparatus was fortunately available, the work was at once undertaken in our Pasadena laboratory by Dr. King. A brilliant spark is produced by a high potential transformer between electrodes supported in the field of a large Du Bois magnet. The light, passing through the pierced pole-pieces, falls on a lens, which forms an image of the spark on the slit of a vertical spectrograph, after reflection on a mirror mounted at an angle of 45° above the slit. This spectrograph, which is precisely similar to the 30-foot spectrograph used with the tower telescope, also stands in a constant temperature well, with the slit about three feet above the floor of the laboratory.[1] It may be used as an instrument of 30 feet focal length, or, as in the present case, a 5-inch (13 cm) objective of 13 feet (4 m) focal length, with a 5-inch plane grating, having 14,438 lines to the inch (567 to the mm), can be swung into the axis of collimation 13 feet below the slit. With this shorter focal length the dispersion in the second or third order of the grating is amply sufficient for the present purpose.

If all of the doublets observed in spot spectra could be photographed in the laboratory, it would be easy to make a satisfactory comparison. Unfortunately, however, most of these lines are very faint in the spark, and as the great majority of them occur in the less refrangible part of the spectrum, exposures of from fifteen to twenty

TABLE I

IRON DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda,\ \text{Spark}}{\Delta\lambda,\ \text{Spot}}$
6213.14	0.703	0.138	0.136	−0.002	5.2
6301.72	0.737	0.144	0.138	−0.006	5.3
6302.71	1.230	0.241	0.252	+0.011	4.9
6337.05	0.895	0.175	0.172	−0.003	5.2

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[1] Hale, "The Pasadena Laboratory of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908.

hours are sometimes required to bring out even the stronger doublets. The results hitherto obtained for the iron doublets are brought together in Table I. I am indebted to Mr. Adams for these measures and for many of the others given in this paper. Miss Burwell and Miss Wickham have also assisted in the measurement of the spot and spark photographs.

The first column gives the wave-length of the doublet; the second, the separation in Ångströms of the components, observed along the lines of force in a field of about 15,000 gausses;[1] the third, the quantity given in column 2 divided by 5.1; the fourth, the separation of the components observed in the spot spectrum; the fifth, the residuals obtained by substracting the quantities in the third column from those in the fourth; the last column gives the ratio of the separation in the spark, for a field of about 15,000 gausses, to the observed separation in the spot. The mean value of this ratio, 5.1, gives an approximate measure of the strength of the field in spots, which comes out about 2900 gausses.

The agreement between the spot and laboratory results is so close that it can hardly be the result of chance. But when we come to the case of titanium, observed in the laboratory in a field of about 12,500 gausses, we find a very different condition of affairs.

TABLE II

Titanium Doublets

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda,\ \text{Spark}}{\Delta\lambda,\ \text{Spot}}$
5903.56	0.732	0.144	0.086	−0.058	8.5
5938.04	0.737	0.145	0.080	−0.065	9.2
6064.85	0.876	0.172	0.184	+0.012	4.8
6303.98	0.493	0.097	0.093	−0.004	5.3
6312.46	0.615	0.121	0.091	−0.030	6.8

If we use the factor 5.1 employed in the case of iron, we find that two of these doublets, λ 6064.85 and λ 6303.98, agree closely in spot and spark. In some of our spot photographs λ 6064.85 appears to be a triplet, though the components are not clearly separated. With the rhomb and Nicol a faint central component persists when either the red or the violet component is cut off. It is possible that this central line is due to some substance other than titanium in the spot, but it is certainly very nearly in the position of the solar titanium line.[1] λ 6312.46 gives a residual of 0.03 Ångströms, which exceeds the error of measurement. The other doublets, λ 5903.56 and λ 5938.04, show in the spot spectrum but little more than one-half the separation that would be expected on the assumption that the strength of the field is the same for all of these lines.

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[1] This value of the field strength may be in error by 1000 gausses, because of the disturbing effect of the iron electrodes.

On consideration it will be seen, however, that the separation of the doublets must depend, in some degree, on the distribution of the absorbing vapor in the solar atmosphere, and on the coefficient of absorption of the particular line employed. A striking instance of this kind, affecting lines of the same series, is illustrated in the case of hydrogen, described in a previous paper.[2] Although the $H\delta$ line extends to the upper part of the chromosphere and prominences, the mean level represented by its absorption is much lower than that given by $H\alpha$. The consequence is that $H\alpha$ enables us to photograph the solar vortices, the characteristic stream lines of which do not appear at the lower $H\delta$ level. Similarly, if the intensity of a given titanium line falls off rapidly, the level represented by this line may be comparatively low. If, on the other hand, its intensity curve is of such a form as to indicate that the absorption at higher elevations plays an important part, the mean level represented by the line may be considerably higher than in the previous case. To settle this question we must know: (1) The range of elevation in the spot of the vapors of iron, titanium, and other elements; (2) the intensities of the lines of these elements at different levels; (3) the rate at which the strength of the field decreases upward.

In the absence of information regarding the first two points, we may inquire as to the probable relative behavior of titanium, iron, and other elements if the distribution of the vapors at different levels were the same as in the chromosphere. From a discussion of a large number of photographs of the flash spectrum, made by different observers at several eclipses, Jewell has compiled a table showing the heights above the sun's limb attained by various lines in the blue and violet.[1] The heights for titanium range from 100 miles (160 km) for λ 4466.0 to 3500 miles (5640 km) for λ 4466.7, while certain strong enhanced lines in the ultra-violet reach elevations of 6000 or 8000 miles (9660 or 12,880 km). For iron the minimum height is 200 miles (320 km) for λ 4482.4 and the maximum 1000 miles (1610 km) for λ 4584.0. Chromium ranges from 100 miles for λ 4280.2 to 1200 miles (1930 km) for λ 4275.0; manganese from "100 miles or more" for λ 4451.8 to "800 miles (1290 km) or more" for λ 4030.9; vanadium from 100 miles for λ 4390.1 to 200 miles for λ 4379.4. It thus appears that the range in level represented by the titanium lines is much greater than for the lines of iron, chromium, manganese, and vanadium. If the vapors were similarly distributed in spots, the maximum strength of field indicated by the titanium lines should therefore correspond with the maximum value for iron, but some titanium lines, produced by absorption at higher mean levels, should give lower field strengths. Chromium should agree more nearly with iron. Vanadium, if the less refrangible lines reach no greater elevations, should give closely accordant (maximum) values for the field strength. It will perhaps be possible, with the aid of the 30-foot spectrograph, to determine the relative levels in the chromosphere attained by most of the lines in question, but it is a much more difficult matter to do this for sun-spots. I hope, however, that our new spectroheliograph of 30-feet focal length may throw some light on this subject.

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[1] It is conceivable that under conditions analogous to those that give rise to the H_3 and K_3 lines, a doublet might be produced within the strong magnetic field of the spot, and a single line, at the center of the doublet, by the absorption of the vapor at a high level, where the field strength is low.

[2] *Solar Vortices*, p. 3.

It is evident that these considerations will have no bearing on the present problem, unless the field strength decreases very rapidly upward in spots. That this probably occurs is shown by the fact that the D lines of sodium and the *b* lines of magnesium are usually but slightly affected in the spot spectrum,[2] and are displaced through a very small distance when the Nicol is rotated. Thus, at the level represented by these lines, which attain elevations in the chromosphere probably not exceeding 5000 miles, the field strength is reduced to a small fraction of its maximum value.

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[1] "Total Solar Eclipses of May 28, 1900, and May 17, 1901," *Publications of the U. S. Naval Observatory*, Second Series, Vol. IV, Appendix I.

[2] Except for the strengthening of the wings, which may be produced by some cause other than a magnetic field.

The following doublets have been measured in the spectrum of chromium:

TABLE III

Chromium Doublets

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{4.9}$	Δλ, Spot	δ	$\frac{\Delta\lambda,\ \text{Spark}}{\Delta\lambda,\ \text{Spot}}$
5304.36	0.636	0.130	0.188	+0.058	3.4
5387.16	0.676	0.138	0.085	−0.043	8.0
5713.00	0.610	0.124	0.161	+0.037	3.7
5781.40	0.755	0.154	0.121	−0.033	6.2
5781.97	0.922	0.188	0.212	+0.024	4.3
5783.29	0.772	0.158	0.137	−0.021	5.6
5784.08	0.720	0.147	0.121	−0.026	6.0
5785.19	0.707	0.144	0.137	−0.007	5.1

In photographing these lines in the spark, the strength of the field was 12,500 gausses. The strength of the field in spots, as indicated by the mean separation of the chromium doublets, is therefore 2600 gausses.

The above tables comprise all of the doublets hitherto observed both in spots and in our laboratory. It was at first hoped that the shifts of lines, on photographs of the spot spectrum made with the rhomb and Nicol, would serve as satisfactory data for comparison with laboratory results. But when the small magnitudes of these shifts, and the wide differences in the character of the lines were taken into account, it appeared that comparisons based on such data could have but little weight.

When a line is clearly resolved into a doublet, rotation of the Nicol cuts off the right-handed or left-handed light, and produces a shift equal to the separation of the components. But when the strength of the field is only sufficient to widen a line, that portion of the widened line where the right-handed and left-handed components overlap is composed of ordinary unpolarized light, not affected by rhomb or Nicol. If the components are narrow, this region may also be narrow. But if they are broad, only the outer edges of the components will be cut off when the Nicol is rotated.

If a magnetic field is the principal cause of the widening of lines in spots, their widths should be roughly proportional to the separation of the components of the corresponding doublets observed in a field of equal strength. Bearing in mind the differences in the character of the lines, and the probable effect of variations in the mean level of absorption, we can hardly expect a very close agreement. But some evidences of relationship should appear, if a magnetic field is present. In the following tables the widths of various iron lines are compared with the separations of their components in the spark. To facilitate the comparison, the distances between the centers of the components, photographed in a field of about 15,000 gausses, are divided by 2.9, which reduces them to approximate equality with the widths in spots.

TABLE IV

Widths of Iron Lines in Spots

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.9}$	Width in Spots	δ
6136.19	0.38	0.13	0.15	+0.02
6137.92	0.50	0.17	0.16	−0.01
6191.78	0.43	0.15	0.14	−0.01
6219.49	0.59	0.20	0.23	+0.03
6246.54	0.67	0.23	0.24	+0.01
6252.77	0.45	0.16	0.15	−0.01
6265.35	0.55	0.19	0.20	+0.01
6315.52	0.59	0.20	0.16	−0.04 Enhanced line
6318.24	0.40	0.14	0.14	0.00
6335.55	0.55	0.19	0.20	+0.01
6393.82	0.46	0.16	0.18	+0.02
6400.22	0.58	0.20	0.22	+0.02
6411.86	0.56	0.19	0.17	−0.02
6417.13	0.69	0.24	0.15	−0.09 Enhanced line
6420.17	0.57	0.20	0.19	−0.01
6421.57	0.64	0.22	0.18	−0.04
6431.07	0.54	0.19	0.19	0.00
6456.60	0.55	0.19	0.22	+0.03 Enhanced line
6495.21	0.54	0.19	0.18	−0.01

The exceptionally large residuals of the enhanced lines may be due to the fact that the weakening of these lines in spots makes them very difficult to measure. But it is perhaps possible that another cause may account for the negative sign of most of their residuals in Tables IV and VI. Assume that in the lower part of spots the field is most intense and the reduction of temperature most marked. In

TABLE V

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda\text{, Spark}}{2.9}$	Width in Spots	δ
5083.58	0.41	0.14	0.15	+0.01
5098.88	0.42	0.14	0.13	−0.01
5107.62	0.25	0.09	0.11	+0.02
5107.82	single*		0.14	
5110.57	0.45	0.15	0.17	+0.02
5123.90	single		0.09	
5125.30	0.41	0.14	0.09	−0.05
5127.53	0.51	0.18	0.15	−0.03
5137.56	0.45	0.15	0.13	−0.02
5139.43	0.56	0.19	0.16	−0.03
5139.64	0.51	0.18	0.15	−0.03
5143.11	0.42	0.14	0.11	−0.03
5162.45	0.47	0.16	0.14	−0.02
5167.68	0.35	0.12	0.12	0.00
5171.78	0.39	0.13	0.15	+0.02
5191.63	0.57	0.20	0.18	−0.02
5192.52	0.56	0.19	0.17	−0.02
5195.11	0.33	0.11	0.14	+0.03
5198.89	single		0.10	
5208.78	0.48	0.16	0.14	−0.02
5215.35	0.45	0.15	0.15	0.00
5216.44	0.23	0.08	0.12	+0.04
5217.55	0.47	0.16	0.15	−0.01
5227.04	0.47	0.16	0.19	+0.03
5227.36	0.32	0.11	0.15	+0.04
5230.03	0.50	0.17	0.15	−0.02
5233.12	0.38	0.13	0.14	+0.01
5242.66	0.29	0.10	0.11	+0.01
5250.82	0.49	0.17	0.14	−0.03
5263.49	0.47	0.16	0.13	−0.03
5266.74	0.38	0.13	0.14	+0.01
5269.72	0.39	0.13	0.15	+0.02
5273.56	0.53	0.18	0.11	−0.07
5276.17	0.31	0.11	0.12	+0.01
5281.97	0.44	0.15	0.11	−0.04
5283.80	0.49	0.17	0.14	−0.03
5302.48	0.48	0.17	0.17	0.00
5316.79	0.32	0.11	0.11	0.00 Enhanced line
5324.37	0.48	0.16	0.16	0.00
5328.24	0.37	0.13	0.17	+0.04
5328.70	0.49	0.17	0.13	−0.04
5340.12	0.48	0.16	0.16	0.00
5365.07	0.30	0.10	0.10	0.00
5367.67	0.31	0.11	0.12	+0.01
5370.17	0.36	0.12	0.12	0.00
5371.73	0.33	0.11	0.16	+0.05
5383.58	0.37	0.13	0.13	0.00
5393.38	0.52	0.18	0.18	0.00
5397.34	0.48	0.16	0.20	+0.04
5400.71	0.42	0.14	0.11	−0.03

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* "Single" in these tables does not mean that the line is not affected by the field, but merely that it was not clearly separated on the plate measured. Several of these photographs were made in the first order.

TABLE V—*Continued*

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{2.9}$	Width in Spots	δ
5404.36	0.38	0.13	0.16	+0.03
5405.99	0.23	0.08	0.15	+0.07
5411.12	0.40	0.14	0.13	−0.01
5415.42	0.38	0.13	0.15	+0.02
5424.29	0.40	0.14	0.15	+0.01
5429.92	0.48	0.16	0.16	0.00
5434.74	single		0.11	
5447.13	0.51	0.18	0.19	+0.01
5455.83	single		0.20	

consequence of the reduced temperature, the enhanced lines are greatly weakened. Hence an unusually large proportion of the absorption which gives rise to these lines may occur at greater elevations, where the temperature is higher and the field weaker. In this case, the field intensities indicated by the enhanced lines should be below the average value. In view of the fact that the rate of change of intensity with level is not the same for all lines, it is evident that many more cases must be included in any satisfactory test of this hypothesis. From the same course of reasoning it follows that lines which are most strengthened in spots should, in general, be most widened. This appears to be true, but a careful quantitative comparison will be made, both for strengthened and weakened lines, and published in a subsequent paper. It must not be forgotten that a considerable increase of temperature in the higher spot vapors would tend to produce true reversals. Discussion of this question must be reserved, however, until the spot spectra can be more thoroughly studied with this point in view.

In Table IV the mean residual, taken without regard to sign, is 0.021 Ångströms. If we omit the enhanced lines, because of their exceptional behavior in spots, the mean residual is reduced to 0.015 Ångströms. As the spot lines range in width from 0.14 to 0.24 Ångströms, the agreement is closer than would be expected to result from chance alone. When it is remembered that one or more secondary causes may also affect the width of the lines, the probability that a true relationship exists appears to be considerably increased.

A more refrangible region of the iron spectrum gives the results detailed in Table V.

Here the mean residual is 0.021 and the range in the width of the spot lines from 0.09 to 0.20 Ångströms. λ 5107.82, λ 5123.90, λ 5198.89, and λ 5434. 74, which are very narrow in spots, are not quite separated on the laboratory plates. λ 5455.83, on the contrary, is single in the laboratory and fairly wide in spots. In this case, at least, there must be some cause of widening in spots other than a magnetic field.

A still more refrangible region of the iron spectrum gives the results contained in the following table:

TABLE VI

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.1}$	Width in Spots	δ
4427.48	0.32	0.15	0.16	+0.01
4433.39	0.28	0.13	0.12	−0.01
4442.51	0.35	0.17	0.18	+0.01
4443.36	0.10	0.05	0.12	+0.07
4454.55	0.26	0.12	0.10	−0.02
4459.30	0.32	0.15	0.12	−0.03
4461.82	0.32	0.15	0.14	−0.01
4466.73	0.26	0.12	0.15	+0.03
4469.54	0.32	0.15	0.12	−0.03
4484.39	0.29	0.14	0.12	−0.02
4494.74	0.25	0.12	0.14	+0.02
4522.80	0.20	0.10	0.08	−0.02 Enhanced line
4525.31	0.32	0.15	0.11	−0.04
4528.80	0.27	0.13	0.13	0.00
4531.33	0.29	0.14	0.12	−0.02
4548.02	0.22	0.10	0.10	0.00
4549.64	0.24	0.11	0.10	−0.01 Enhanced line
4556.06	0.27	0.13	0.12	−0.01 Enhanced line
4603.13	0.37	0.18	0.14	−0.04

It is interesting to note the progressive decrease toward the violet in the mean width of spot lines and the separation of the corresponding doublets in the spark, as shown by the following table. The (weighted) means represent the three groups of lines given in Tables IV, V, and VI.

TABLE VII

Mean Wave-Length	Spot Lines Mean Width	Spark Doublets Mean Separation
6330	0.18	0.54
5267	0.14	0.42
4495	0.13	0.29

Although the rate of decrease is more rapid for the spark doublets than for the spot lines, it must be remembered that in the former case the mean separation of the components is given, while the mean width of the spot lines represents the separation of the components plus their width. The width of the components cannot be determined, except in the case of doublets, and therefore the rate of decrease falls off toward the violet, as the width of the spot lines approaches that of the solar lines. The extremely small average shift of the lines in the violet when the Nicol is rotated is in harmony with this view.

A group of twelve spot doublets near λ 4395, which belong to several different elements and have not yet been photographed in our laboratory, afford some additional evidence. The mean separations of groups of spot doublets in the red (Tables I, *Fe*, and II, *Ti*), green (Table III, *Cr*), and violet (those just mentioned) are given in the following table:

TABLE VIII

MEAN WAVE-LENGTH	SPOT DOUBLETS	
	Number	Mean Separation
6186	9	0.137
5665	8	0.145
4395	12	0.085

Between λ 6186 and λ 5665 these doublets show no such progressive change as appears in Table VII.

Preston's law, $\frac{\Delta\lambda}{\lambda^2}=\text{const.}$, has been found to hold rigorously only for the lines of certain series. It therefore could not be expected to apply with accuracy here, especially as the lines of different elements are included. Nevertheless it is of interest to determine whether the decrease in the separation of these doublets toward the violet proceeds at a similar rate. If we combine the separations for λ 6186 and λ 5665, we have 0.141 for the mean wave-length λ 5941. Then

$$\frac{0.141}{(5941)^2}=4.0\times 10^{-9}$$

$$\frac{0.085}{(4395)^2}=4.4\times 10^{-9}.$$

The iron doublets, whose mean separations for a field strength of about 15,000 gausses are given in Table VII, yield the following results.

$$\frac{0.44}{(5544)^2}=14.3\times10^{-9}$$

$$\frac{0.29}{(4495)^2}=14.3\times10^{-9}.$$

Thus the iron doublets follow the law very closely, while the approximate agreement with the spot doublets, though perhaps the result of chance, is not without interest.

Table IX gives the widths of various titanium lines in spots, and the separations of the components of the corresponding doublets, observed along the lines of force in a field of 12,500 gausses.

TABLE IX

WIDTHS OF TITANIUM LINES

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{3.4}$	Width in Spots	δ
5823.91	single		0.13	
5866.68	0.48	0.14	0.19	+0.05
5880.49	0.64	0.19	0.19	0.00
5899.52	0.50	0.15	0.18	+0.03
5903.56	0.73	0.21	0.19	−0.02
5918.77	0.73	0.21	0.20	−0.01
5922.33	single		0.12	
5938.04	0.74	0.22	0.17	−0.05
5953.39	0.52	0.15	0.13	−0.02
5966.06	0.47	0.14	0.16	+0.02
5978.77	0.38	0.11	0.14	+0.03
6064.85	0.88	0.26	0.27	+0.01
6085.47	0.81	0.24	0.20	−0.04
6091.40	0.65	0.19	0.15	−0.04
6092.74	0.55	0.16	0.16	0.00
6098.87	0.59	0.17	0.15	−0.02
6121.22	0.56	0.16	0.17	+0.01
6126.44	0.64	0.19	0.17	−0.02
6146.44	single		0.12	
6261.32	0.41	0.12	0.16	+0.04
6317.67	0.42	0.12	0.12	0.00
6336.33	0.56	0.16	0.15	−0.01
6366.56	0.55	0.16	0.18	+0.02

For titanium in this region the mean residual is 0.021 Ångströms for spot lines ranging in width from 0.12 to 0.27 Ångströms.

SIGN OF THE CHARGE THAT PRODUCES THE FIELD IN SUN-SPOTS

If the evidence presented in this paper renders probable the existence of a magnetic field in sun-spots, it is of interest to inquire concerning the sign of the charge which, according to our hypothesis, produces the field. In Lorentz's theory of the Zeeman effect in its simplest form, the motion of a single electron in a molecule of a luminous source is discussed.[1] This electron is supposed to be capable of displacement in all directions from its position of equilibrium, toward which it is drawn by an elastic force, which is proportional to the displacement but independent of its direction. Let e be the charge of the particle, m its mass, fr the elastic force caused by a displacement r, f being a positive constant. The frequency of the vibrations, whether they be linear, elliptical, or circular, will be

$$n_0 = \sqrt{\frac{f}{m}}\,.$$

We may now suppose the light-source to be placed in a homogeneous magnetic field of intensity H. A particle carrying a charge e, and moving with velocity v, will be subjected to a force perpendicular to the field and to the direction of motion of the particle, the magnitude of which may be represented by $ev\mathrm{H}\sin(v, \mathrm{H})$. It is evident that the electron may have three different motions, each with its own frequency. Linear vibrations parallel to the lines of force, having the frequency n_0, will not be affected by the magnetic field. Circular vibrations in a plane perpendicular to the lines of force will be affected differently, depending upon whether they are right-handed or left-handed. If r is the radius of a circular orbit and n the frequency, the velocity of the electron will be $v=nr$ and the centripetal force will have the value mn^2r. We may now consider the effect on the motion of the electron of the elastic force fr and of an electromagnetic force

$$ev\mathrm{H} = enr\mathrm{H}.$$

For a positive charge the latter force is directed toward the center if the motion is clockwise, as seen by an observer toward whom the lines of force are directed. We then have

$$mn^2r = fr + enr\mathrm{H}.$$

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[1] The following outline of the theory is taken from Lorentz's "Theorie des phénomènes magnéto-optiques récemment découverts," *Rapports,* Congrès international de physique, **3**, 1, 1900.

This frequency n differs very slightly from the frequency n_0; thus the last term of the equation must be much smaller than the term fr, so that we may write

$$n=n_0+\frac{eH}{2m}. \tag{1}$$

This expression gives the frequency of the right-handed (clockwise) vibrations. For the left-handed vibrations we have

$$n=n_0-\frac{eH}{2m}. \tag{2}$$

As seen along the lines of force a single line in the spectrum is thus transformed into a doublet, the components of which are circularly polarized. An observer toward whom the lines of force are directed will find that the light of the component of greater wave-length, whose frequency has been decreased by the field, is circularly polarized in the right-handed or clockwise direction. Hence (2) is greater than (1), and it follows that the charge e of the electron which produces the spectral lines must be negative.

In the case of the solar vortices we have to consider two sets of charged particles, which may be entirely distinct from one another: (1) those whose vibrations give rise to the lines in the spectra of spots, and (2) those that carry the charge which, by the hypothesis, produces the magnetic field. The Zeeman effect supplies the means of determining the direction of the lines of force of the sun-spot fields, and photographs of the vortices, made with the spectroheliograph, indicate the direction of revolution of the particles. Thus we are in a position to determine the sign of the charge carried by the particles which produce the fields. As pointed out independently by König and Cornu, the violet component of a magnetic doublet observed along the lines of force is formed by circular vibrations, having the direction of the current flowing through the coils of the magnet.[1] From observations of circularly polarized light, made in our Mount Wilson laboratory by Dr. St. John and confirmed by myself, it appears that when the Nicol prism of the tower spectrograph stands at 60° E. it transmits the violet component of a doublet produced in a magnetic field directed toward the observer. From Biot and Savart's law the direction of the current causing such a field is counter-clockwise, as seen by the observer. In the same position the Nicol also transmits the violet component of a doublet produced in a sun-spot surrounded by a vortex in which the direction of revolution is clockwise. As a negative charge revolving clockwise produces a field of the same polarity as an electric current flowing counter-clockwise, we may conclude that the magnetic field in spots is caused by the motion of negative corpuscles.

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[1] See Cotton, *Le phénomène de Zeeman*, chap. vii; König, *Wied. Ann.*, **62**, 240, 1897.

PROBABLE SOURCE OF THE NEGATIVE CORPUSCLES

We may now consider the probable source of a sufficient number of negative corpuscles to produce a field of about 2900 gausses in sun-spots.

In his *Conduction of Electricity through Gases*, p. 164, J. J. Thomson writes as follows:

> We thus are led to the conclusion that from an incandescent metal or glowing piece of carbon "corpuscles" are projected, and though we have as yet no exact measurements for carbon, the rate of emission must, by comparison with the known much smaller rate for platinum, amount in the case of a carbon filament at its highest point of incandescence to a current equal to several amperes per square centimeter of surface. This fact may have an important application to some cosmical phenomena, since, according to the generally received opinion, the photosphere of the sun contains large quantities of glowing carbon; this carbon will emit corpuscles unless the sun by the loss of its corpuscles at an earlier stage has acquired such a large charge of positive electricity that the attraction of this is sufficient to prevent the negatively electrified particles from getting right away from the sun; yet even in this case, if the temperature were from any cause to rise above its average value, corpuscles would stream away from the sun into the surrounding space.

On another page (168) Thomson also remarks: "The emission of the negative corpuscles from heated substances is not, I think, confined to the solid state, but is a property of the atom in whatever state of physical aggregation it may occur, including the gaseous." After illustrating this in the case of sodium vapor, Thomson adds (p. 168):

> The emission of the negatively electrified corpuscles from sodium atoms is conspicuous as it occurs at an exceptionally low temperature; that this emission occurs in other cases although at very much higher temperatures is, I think, shown by the conductivity of very hot gases (or at any rate by that part of it which is not due to ionization occurring at the surface of glowing metals), and especially by the very high velocity possessed by the negative ions in the case

of these gases; the emission of negatively electrified corpuscles from atoms at a very high temperature is thus a property of a very large number of elements, possibly of all.

Thus the chromosphere, as well as the photosphere, may be regarded as copious sources of negatively electrified corpuscles. The part played by these corpuscles in sun-spots cannot be advantageously discussed until the nature of the vortices is better understood.[1] At present it is enough to recognize that the supply of negative electricity appears amply sufficient to account for the magnetic fields.

Let n be the number of corpuscles per unit cross-section passing a given point in unit time and e the charge on each corpuscle. Then we have, for the current carried by the corpuscles, $c=ne$. H. A. Wilson found that in a vacuum tube, at pressures up to 8.5 mm, the current at the cathode was $0.4\,p$ milliamperes per sq. cm, where p is the pressure in millimeters.[2] If $p=8.5$, we have $c=3.4\times 10^{-3}$ amperes. Assume the velocity of the corpuscles in this case to be of the order of 10^4 km per sec. In a solar vortex (if the charged particles are carried with it) the velocity may be taken as of the order of 100 km per sec.[3] Then if the number of corpuscles per sq. cm were the same in the two cases, the current in the sun would be of the order of 3.4×10^{-5} amperes per sq. cm at the same pressure.

We may now assume the corpuscles to be moving at a velocity of 100 km per second in an annulus 25,000 km wide, 1000 km deep, and 100,000 km in diameter surrounding a sun-spot. Taking the current strength to be as above, 3.4×10^{-5} amperes per sq. cm, the intensity of the resulting magnetic field comes out 1000 gausses.

Such a calculation is of little value, except for the purpose of indicating that a magnetic field of the observed order of magnitude might conceivably be produced on the sun.[4]

EXTERNAL FIELD OF SUN-SPOTS

We have already seen that the strength of the field in spots apparently changes very rapidly along a solar radius, and is small at the upper level of the chromosphere.

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[1] For this reason a discussion of the very interesting suggestion of Professor E. F. Nichols, that the positively and negatively charged particles are separated by centrifugal action in the spot vortex, is reserved for a subsequent paper.

[2] *Philosophical Magazine* (6), **4**, 613, 1902.

[3] *Solar Vortices*, p. 13.

[4] See a similar calculation by Zeeman in *Nature* for August 20, 1908.

If subsequent work proves this to be the case, it will appear very improbable (as indicated by theory) that terrestrial magnetic storms are caused by the direct effect of the magnetic fields in sun-spots. We have some reason to think that their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots.

CONCLUSION

Although the combined evidence presented in this paper seems to indicate the probable existence of a magnetic field in sun-spots, the weak points of the argument should be clearly recognized. Among these are the following:

1. The failure of our photographs to show the central line of spot triplets before the spots are very close to the limb.
2. The absence of evidence to support the hypothesis that the imperfect agreement between spot and laboratory results is due to differences in the mean level of absorption.
3. The apparent constancy of the field strength, as indicated by the nearly uniform width of the doublets in different spots.
4. The difficulty of explaining, on the basis of our present fragmentary knowledge of solar vortices, the observed strength of field in the umbra and penumbra, and especially its variation with level.

As the resolving power of the 30-foot spectrograph is sufficient to resolve completely only the wider spot doublets, the central line could not be separately distinguished in other cases, even if it were present. Hitherto it has been possible to photograph the spectra of only the largest spots, because the images of other spots, as given by the tower telescope, are too small. The need of a telescope giving a much larger image of the sun, and a spectrograph of greater resolving power and focal length, which has been felt in previous work, is strongly emphasized by this investigation. Such apparatus would also permit the spectrum of the chromosphere, and many other solar phenomena, to be studied to great advantage.

As regards the nature of the vortices, the principal question is whether the gyratory motion primarily concerned in the production of the magnetic field is outside the boundaries of the spot or within the umbra. In the former case we must face various difficulties, such as the apparent constancy of the field in different spots, and the fact that its intensity rapidly decreases upward. The view that the field is produced by the gyratory motion of vapors within the umbra raises other difficulties, which may also be serious. Fortunately there is reason to hope that observations now in progress may throw light on several of these questions.

Mount Wilson Solar Observatory
October 7, 1908

ADDENDUM

The fact that the doublets in the sun-spot spectrum do not change to triplets, even when the spot is as much as 60° from the center of the sun, appeared, when the proof of the above paper was corrected, to be a serious argument against the magnetic field hypothesis. Thanks to the recent work of Dr. King, this difficulty no longer exists, at least in the case of several iron and titanium lines. Photographs of the spark spectrum in a strong magnetic field, taken at right angles to the lines of force, show that the iron lines $\lambda\lambda$ 6213.14, 6301.72, and 6337.05 are doublets,[1] with no trace of a central component. As these lines are also doublets when observed parallel to the lines of force, it is only natural that they should be double in spots, wherever situated on the solar disk. λ 6173.55, which is a fine triplet in spots, is a triplet when observed at right angles to the lines of force. λ 6302.71 is a triplet, though in Table I it is classed as a spot doublet. In the spot spectrum the line is a triplet, but so decidedly asymmetrical in appearance that I supposed the intermediate line to be due to some element other than iron, greatly strengthened in the spot. It now turns out, however, that the apparent asymmetry is due to a line of some other substance, which occurs in the spot spectrum. In the laboratory this triplet is symmetrical, though the overlapping component of an adjoining line gave an appearance of asymmetry in the earlier photographs.[2]

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[1] Later results prove these to be quadruplets, with the components of each member of the doublets too close for resolution in the spot spectrum.

[2] The triplet λ 6302.71 was incorrectly described in this paper, as printed in the *Astrophysical Journal* for November 1908. The data given above have been derived from later and better photographs.

The titanium lines $\lambda\lambda$ 6303.98 and 6312.46, which are double in spots, are also double in the spark, when observed at right angles to the lines of force.[1] λ 6064.85, already mentioned as a triplet in spots, with a rather faint central component, is a triplet, with strong central component, in the spark under the above conditions.

The titanium spot doublets $\lambda\lambda$ 5903.56 and 5938.04 (Table II) have not yet been observed at right angles to the lines of force.

These results leave no doubt in my mind that the doublets and triplets in the sun-spot spectrum are actually due to a magnetic field. As I am now designing a spectrograph of 75 feet (23 m) focal length, for use with a tower telescope of 150 feet (46 m) focal length, I hope it may become possible to investigate small spots, as well as large ones, and to resolve many of the close doublets and triplets in their spectra.

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[1] Later results prove these to be quadruplets, with the components of each member of the doublets too close for resolution in the spot spectrum.

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